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LIGHT SOURCES FOR REMOTE SENSING SYSTEMS

by M. W. P. Cann

Prepared by
IIT RESEARCH INSTITUTE
Chicago, Ill.
for George C. Marshall Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1967

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FOREWORD

This study was undertaken for the National Aeronautics and Space Administration, under Contract NAS8-20107, for the purpose of investigating the availability of suitable commercial light sources for remote sensing systems. The study commenced by soliciting information from manufacturing companies, informing them by letter of the purpose of the study and the light source properties sought. The replies received varied over a wide range in information content and more information was requested from some companies. Information was also obtained from the literature and research workers using commercial sources. The wide disparity in the responses of the various companies, especially those marketing similar sources, has led to unavoidable emphasis of some companies' products in this report. In an attempt to offset this effect, indication is given wherever insufficient information was obtained from a particular company. Critical comparisons between similar products of different companies have been avoided as far as possible and are mostly limited to tabulations of light source properties, obtained from the company literature; it was not the purpose of this study to make such comparisons.

ABSTRACT

Light sources for remote sensing systems must fulfill certain criteria, which have been discussed by Montgomery.[1] The present report reviews the available light sources in the spectral range 150 to 2000 nm (nanometers). Attention has been confined to sources which are either DC or operate at frequencies in excess of 1 MHz; the properties investigated were spectral intensity distribution, uniformity of emission over source area and emission angle, stability and life. Some attention has been given to light sources described in the literature where these fulfil a need not met by those available commercially. The report presents intercomparisons between different types of sources but generally not between sources of the same type from different manufacturers, although listings of the properties of the commercial sources (obtained from company literature) are given.

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1. INTRODUCTION

This survey was undertaken expressly for the purpose of investigating the availability of suitable light sources for use in remote sensing systems, for the spectral range 150 to 2000 nm. The particular system envisaged employs two crossed light beams which interact with the medium through which they pass before being monitored by suitable detectors, the outputs of which are correlated to extract data on non-random fluctuations of properties in the light paths.[2,3] These applications determine a set of strict requirements in prospective sources and provided the guidelines for the survey. Montgomery[1] has given the light source criteria and discussed the factors conditioning their choice. This report is primarily a survey of commercially available light sources but consideration was given to others in special cases.

At the start of the survey over 130 manufacturing companies were solicited for information on their light source products. Many of these made sources intended for industry and the general consumer and were not of interest. Many others did not reply and only the most promising of these were pursued. It very soon became apparent that the manufacturers' literature seldom provided data which could be fitted against any of the selected criteria (see p. 134). Hence, the technical literature was studied in an attempt to fill in the gaps; also several laboratories, using the commercial sources, and research workers, who in some cases had made special sources for their own work, were approached for more information. These three sources of information provided the data for the report which follows.

The terms of the survey dictated a study of commercial sources only. However, in some cases it was apparent that laboratory-constructed sources should be included either because they had superior stability, or on account of a high intensity where there was a dearth of strong commercial sources -- the argon arc is an example which, as is shown in this report, may well provide an ultraviolet source with an intensity greatly exceeding currently available commercial sources.

A.C. and other low-frequency discharges have been omitted, concurring with the frequency limit of 1 MHz. (p. 134) This has caused the exclusion of many otherwise useful sources, compact arcs, capillary arcs (e.g. General Electric, PEK Labs.) and repetitively pulsed discharges (e.g. those used by Huffman, Tanaka and Larrabee, in generation of intense continua for the vacuum ultraviolet[4]).

Various surveys of light sources have been made in the past and the present effort has profited from them, notably those by Koller[5], Carlson and Clark,[6] and Samson.[7] Carlson and Clark give data on many sources not treated here, including A.C. and pulsed sources, thus complementing this report. Samson's report covers th vacuum ultraviolet, a region which is here considered down to 150 n only, whereas Koller deals with ultraviolet sources generally.

This report does not give a fair comparison between similar sources made by different manufacturers and is not intended as such, it is simply a study of the types of source available. Some manufacturers responded with copious information on their products, others were more parsimonious (e.g. the sections on compact arcs consider the Hanovia lamps in much more detail than any other manufacturer's, because appreciably more data were received on this company's products. Westinghouse compact arcs are barely discussed because the information could not be obtained).

The various sections discuss the different types of sources. Line sources are given brief mention only, primarily because of the limited time available for the survey. The types of commercially available lasers are mentioned but the properties of laser beams have not been discussed, the laser literature should provide ready access to such information.

In Section 5, sources for the ultraviolet, visible and infrared are compared in terms of their spectral steradiancies. The data curves presented give only an order of magnitude comparison on account of the uncertainties in the methods of measurement, source area definition etc., used by the various authors. Section 6 shows the extent to which the available type of sources meet the requirements for remote sensing systems. These two sections provide a guide to the light sources available; more data are contained in the respective sections of the text, with references to source material which may be used to make further estimates where desired.

2. ARCS

2.1 Introduction

Arcs in one form or another are finding wide application in many industries and research laboratories. Commercially available arcs are, however, essentially limited to three kinds:

i) Compact arcs - small encapsulated arcs in gases, usually at high pressures

ii) Carbon arcs

iii) Plasma jets - for use in industry or in laboratories.

With the possible exception of (i), these arcs were not developed for the high stability which is required for the applications discussed in this report; there is an exception in a particular carbon arc as will be mentioned later. In view of the very high radiance of arcs, and the importance of this property in remote sensing applications, it was considered worthwhile to include a discussion of a few arcs which have been constructed in various laboratories but are not available commercially. These have been constructed for special purposes and may have application in remote sensing studies; in the main, however, they are very inconvenient to use on account of size, power requirements, water cooling, gas flow etc.

Arc discharges are characterized by high currents, high temperatures and large electron densities. In consequence of their high temperatures, they radiate strongly but are not usually optically thick, so that the emitted radiation is weaker than the Planck law would predict for such temperatures. On account of the radiating gas being optically thin, in many cases the hot electrodes contribute appreciably to the total radiation emitted by the source. The radiation is characterized by lines and bands overlapping a strong continuum, which is caused by free-free and free-bound electron transitions, in addition to the contribution from incandescent electrodes; hence, the strength of the continuum emission is a consequence of the high electron density. Finkelnburg and Maecker,[8] Maecker[9] and Lochte-Holtgreven[10] have published descriptions and discussions of the many different kinds of arcs which have been studied.

There are many different ways to classify arcs, e.g. temperature range, power level, gas density, gas type, stabilizing mechanism etc., and these can be found in the references cited (see also other authors in reference (9)). The comprehensive coverage that would follow such a classification will not be given here since most of these arcs exhibit fluctuations and instabilities which lie well outside the required tolerances (see Section 6). Indeed, it is only by exercising considerable effort that highly stable arc sources can be constructed, and the great majority of arcs mentioned in the literature were probably not built with such stability levels in mind.

The discussion which follows is limited to commercially available arcs and a few laboratory arcs which have special merit in the present application.

2.2 Compact Arcs

2.2-1 General

These are lamps in which the arc is contained within a fused quartz envelope, with the gas or vapor fill at a high pressure during operation (20 to 40 atmospheres). The high pressure results in a higher luminous (visible) efficiency. There are also some capillary arcs available which operate at pressures of up to 240 atmospheres, close to the limit set by the quartz envelope. The early history and construction of mercury vapor lamps is given by Elenbaas[11] and, for xenon lamps, by Cumming.[12,13]

A primary difficulty in evaluating these arcs is the fact that they were developed for illumination purposes and so the available data are for the visible region almost exclusively. These data are usually expressed in photometric terms and so have been averaged over the photopic response of the eye.

The following manufacturers were contacted during this study for information on lamps produced by them

1. Associated Electrical Industries, U.K.
   Kelvin and Hughes American Corp., Annapolis, Md.

2. Engelhard Industries, Inc., Hanovia Lamp Division
   Newark, N. J.
3. General Electric Company, Large Lamp Division,
   Cleveland, Ohio
4. N. V. Philips Gloeilampen fabrieken, Netherlands,
   North American Philips Company Inc., New York, N.Y.
5. Osram GmbH, Germany
   Macbeth Sales Corporation, Newburgh, N.Y.
6. PEK Laboratories, Inc., Sunnyvale, California
7. Sylvania Electric Products Inc., Ipswich, Mass.
8. Westinghouse Electric Corporation, Lamp Division,
   Bloomfield, N.J.

Of the above manufacturers, Philips (Eindhoven) did not forward any information, stating that they were unable to help; it was not established whether they market such sources in the U.S. or not. AEI (U.K.) furnished incomplete and almost useless information. These two manufacturers were not, therefore, considered further in this study. On the other hand, Engelhard Industries and Osram were particularly helpful in forwarding information they had and in discussing aspects on which they did not have the required data.

Other manufacturers, than the above, supply these lamps with specially built housings of various kinds, with cooling systems, power supplies and other accessories, e.g.

Orion Optics Corp., Stamford, Connecticut

Rudolph Instruments Engineering Co., Inc.

Little Falls, New Jersey

Schoeffel Instrument Co., Westwood, New Jersey

These companies use Hanovia and Osram lamps.

Compact arc lamps are widely used and many different types are available. In this report comparisons and deductions are presented which have been made from the data obtained; in addition, data pertaining to unusual operating conditions have been included. Some companies did not furnish as much data as others so that it was impossible to make proper comparisons between the compact arcs of different manufacturers, only between compact arcs and other types of sources.

The high radiancy of these arcs is due to their high temperatures. The mercury vapor arc, for example, operates at temperatures in the range 5000-7000°K, and the xenon arc has a color temperature of around 6000°K. Osram[14] gave a color temperature in the region 6200-6500°K at the center of a xenon arc with a true temperature around 9000°K, the hottest regions could be higher. These figures are presumably those obtained by Schirmer,[15] although this was not explicitly stated.

The standard lamps are made with three different gas or vapor fills:

i) Xenon

ii) Mercury and xenon, or mercury and argon

iii) Mercury

The last appears to be rare but the extent to which these are made wasn't ascertained with certainty, lamps listed as having a mercury fill often have the rare gas as well, to assist in starting. These lamps have quite different spectral characteristics, as will be seen in Section 2.2-3.

Short arc lamps are currently available for operation in the power range (electrical) 35 to 7,500 watts. The dimensions differ but the overall construction principles are the same. The electrodes are of tungsten: thoriated tungsten is used in some of the higher power lamps. Various electrode shapes are used and have an appreciable influence on the radiative output characteristics. Since the anode gets appreciably hotter than the cathode, it is usually made substantially larger, with a rounded contour. The brightest regions of the arc are near the cathode when this has a pointed configuration.

The orientation at which these lamps may be used is primarily dictated by heat transfer considerations - in most lamps the anode must be up and the lamp operated within a few degrees of the vertical. Operation in the horizontal position is possible for many arcs, if necessary, but with a considerably shorter life.[16,17] Apart from the danger of local overheating and rupture, the envelope is quickly coated with tungsten from the electrodes. The operating position will also affect the distribution of the emitted radiation. The effect is due to the tail flame of the hot convected gases from the arc which, with the vertical arc is dispersed by the top electrode but, with a horizontal arc, distorts the arc image. Results with a 2500 watt xenon lamp showed a shorter life but only a small arc deflection.

Tables I-A, I-B, I-C give a comparative listing of the compact arc lamps for which information was received. The following letter prefixes were used to denote manufacturer and originated in this report, they do not appear in the manufacturers listing

GE	General Electric Corporation
Ha	Engelhard Industries (Hanovia Lamp Division)
PEK	PEK Labs. Inc.
Om	Osram GmbH
Sa	Sylvania Electric Products Inc.
WE	Westinghouse Electric Corporation

Lamps made by Associated Electrical Industries, U.K., and marketed in the U.S. have been omitted for reasons given earlier. They were lamps operating at power levels of 250, 500, 1000 and 1750 watts.

The data received from Westinghouse were printed in 1964. In their brochure they state that development work on lamps from 200 to 10,000 watts was in progress. In addition to the brochure, Westinghouse supplied a copy of a paper by Freeman and Alameda[18] in which two other lamps were described. Apart from these two

TABLE I A COMPARATIVE TABLE OF HIGH PRESSURE ARC LAMPS

Up to 500 Watts

Power (watts)	Lamp Designation	Lamp Fill	Arc Length (mm)	Brightness (Av) (Candles. mm^{-2})	Life (Av) (hours)
30	Ha: 919B1	Xe/Hg	0.4	36	100
35	PEK X-35	Xe	0.3	400	200
75	PEK X-75	Xe	0.375	800	300
75	Om: XBO 75W	Xe	0.5	400	400
80	Ha: 971C	Xe	0.4	250	100
80	Ha: 448C	Xe	0.5	500 (2500)(5)	
100	PEK 110	Hg	0.3	1,400	100
100	Om: HBO 100W	Hg	0.25	1,700	200(2)
100	Sa: HGK 100	Ar/Hg	0.51		100
150	Ha: 901C1	Xe	1.4	96	1,000
150	PEK X-150	Xe	1.27	300	500
150	Om: XBO 150W	Xe	2.2	150	1,200
200	Ha: 901B1	Xe/Hg	1.4	190 (1,200)(4)	1,000
200	PEK 202	Hg (3)	2.5	250	200
200	PEK X-200	Xe	1.5		150
200	Om: HBO 200W	Hg	2.2	330	400(2)
200	Sa: HGK 200	Ar/Hg	2.46		200
250	Om: XBO 250W	Xe	1.7	260	1,200
250	WE: SAH 250B	Hg	2.5	250	600
300	Ha: 914C1	Xe	1.5	540 (1530)	1,000
300	PEK X-300	Xe	2.0	350	300
450	Om: XBO 450W	Xe	2.7	350	2,000
500	GE: XE 500T14	Xe	2.5	(2500)	1,500

1. Can be operated horizontally
2. Life is halved with three electrode version
3. Contains 1/2 atm. Ar
4. 1120 when operated horizontally
5. Maximum values in brackets

TABLE I B COMPARATIVE TABLE OF HIGH PRESSURE ARC LAMPS

(500 to 2000 Watts)

Power (watts)	Lamp Designation	Lamp Fill	Arc Length (mm)	Brightness (Av) (Candles mm^{-2})	Life (Av) (hours)
500	Ha: 959C	Xe	0.6	4,000 (5,400)[4]	200
500	PEK 500-2	Hg	4.3	220	300
500	PEK X-500	Xe	2.5	350 (450)	500
500	Om: HBO 500W	Hg	4.1	300	400
600	Ha: 970C1	Xe	2	360	1,000
900	Ha: 538C9	Xe	5	110 (1,000)	1,000
900	Om: XBO 900W	Xe	3.3	550	2,000
900	GE: B-H6 (Capillary)	Hg/Ar	25		40
1000	Ha: 528B9	Xe/Hg	5	150 (700)	1,000
1000	PEK X-1000	Xe	3.5	600 (750)	2,000
1000	PEK Capillary				
	Type C[5]	Hg	28.6	400	60
	Type A-H6 [5]	Hg	25.4	400	60
	Type B-H6	Hg	25.4	400	60
1000	Ge: A-H6 (Capillary)[5]	Hg/Ar	25		75
1500	PEK Capillary				
	Type B [5]	Hg	28.6	600	10
1600	PEK X-1600	Xe	4.2	750 (900)	2,000
1600	Om: XBO 160W	Xe	4.0	650	2,000

1. Can be operated vertically

2. Life halved with three electrode version

3. Maker lists the maximum given in brackets

5. Requires water cooling

TABLE I C COMPARATIVE TABLE OF HIGH PRESSURE ARC LAMPS
(2000 Watt Upwards)

Power (Watts)	Lamp Designation	Lamp Fill	Arc Length (mm)	Brightness (Av) (Candles. mm^{-2})	Life (Av) (hours)
2000	PEK Capillary Type A(5)	Hg	28.6	900	5
2200	Ha: 491C39	Xe	4.5	500	1,000
2200	Ha: 491C1	Xe	4.5		
2500	Ha: 929B9U	Xe/Hg	5	540	1,000
2500	PEK X-2500	Xe	5.8	650 (750)[4]	1,500
2500	Om: XBO 2500W	Xe	6.0	610	1,500
2500	WE: SAHX 2500B	Xe/Hg	6.0	1,300	400
5000	Ha: 966C39	Xe	7.5	700	1,000
5000	Ha: 932B39	Xe/Hg	5.5	780	500
5000	PEK X-5000	Xe	7.6	720 (950)	500
5000	GE: XE 5000	Xe	8	870 (5,900)	1,000
6500	Om: XBO 6500W (6)	Xe	9	950	No Data
7500	PEK X-7500	Xe	9.5	850 (1000)	500

4. Maker lists the maximum given in brackets
5. Requires water cooling
6. Preliminary specifications

sources, no other information on Westinghouse lamps was obtained, in spite of requests made. The brochure indicated, however, that Westinghouse does make other lamps of this kind. A discussion of the design of the 5-10 Kwatt lamps is given by Freeman[19] and emphasizes the problem of forced air cooling of high powered lamps, but this information is now old.

General Electric supplied information on two short-arc lamps and it appears that this is all they make at present. They also make two types of high pressure capillary arcs and these are listed in the Tables. These capillary arcs are filled to 1/15 atm of argon but, on vaporization of the mercury, operate at 110 atmospheres. Under operating conditions the envelope tends to de-vitrify, with a loss in the light emitted - this tendency may vary appreciably from one particular lamp to another, the reason is not known. These arcs are normally operated on A.C., the possibility of D.C. operation was not verified. The 5 Kwatt XE5000 General Electric compact arc has been discussed in some detail by Breeding.[20]

Details obtained from manufacturers on their lamps (D.C. only) are given in Tables II-A, to II-G. These tables are intended as a guide to the types of lamp available; the products marketed are bound to change with time so the manufacturers should be consulted for the latest information. The Osram lamps listed in Table II-e include the XBF 6000W which is water cooled. According to the Macbeth Sales Corporation, which handles Osram products in the U.S., the XBF series can be used on A.C. or D.C., although the Osram literature indicate D.C. only. There are two other such lamps not shown in the Table, XBF 1000 W and XBF 2500 W.

Operation of short-arc lamps at higher than the rated power is possible but with reduced life, e.g. the Hanovia 491C xenon lamp, rated at 2.2 Kwatts, has been operated at 4 Kwatts for 15 second periods and at 20 Kwatts for periods of 0.1 second.[10] Laue[21] reports that operation of a 5 Kwatt lamp at 6 Kwatts reduced the useful lamp life from 400 to 100 hours and Osram passed on the following information[14] which had been found by their customers,

i) XBO 1600 W. Pulses of 0.15 second duration of 700 amps (rated for 75 amps). After approximately 750 pulses the electrodes showed a heavy cauliflower pattern; the arc stability decreases but the envelope was barely blackened.

ii) XBO 2500 W. Pulses of approximately 0.02 sec. duraction, 1200 amps (rates for 95 amps). After about 1000 pulses the lamp was unusable.

Osram stated that the lamps would stand a higher number of pulses when not so strongly overloaded and recommended operating the lamp at a low D.C. level, superimposing the excess current pulse; the mean power should not exceed the rated maximum.

For some applications there are advantages in operating such lamps in a vacuum. This usually leads to rupture, however,

TABLE II A GENERAL ELECTRIC COMPACT LAMPS

		XE 500T14 (1)	XE 5000 (3)	BH6 (6)	AH6 (5) (6)
Lamp Fill		Xe	Xe	Hg/Ar	Hg/Ar
Lamp Power	watts	500	5000	900	1000
Operating Voltage	volts	20	345	840	840
Operating Current	amps	25	145	1.2	1.45
Arc Gap (Cold)	mm	2.5	8	25	25
Brightness (max)	cd. mm^{-2}	2500	5900	300	300
Output	lumens		275,000	60,000	65,000
Burning Position		Base Down	Anode up (2)		
Overall Length	inches	6½	19½		
Life	hours	1500		40 (4)	75

(1) Developmental - preliminary data dated June 14, 1965

(2) Vertical ± 10°

(3) Cool with air jets on bases

(4) Based on 25 min. operating periods

(5) Water Cooled

(6) Capillary arcs, normally operated on A.C.

TABLE II-b

DATA ON HANOVIA LAMPS

		919B1	971C (3 Electrodes)	901C1	901B1	914C1	959C	970C1	538C9	528B9	491C39	929B9	966C39	932B39	448C
Wattage	Watts	30	80	150	200	300	500	450 to 600	900	1000	2200	2500	5000	5000	80
Gas-Filling	Xe Xe/Hg	Xe/Hg	Xe	Xe	Xe/Hg	Xe	Xe	Xe	Xe	XeHg	Xe	Xe/Hg	Xe	Xe/Hg	Xe
Arc-Length mm	Hot	.3-.4	.3-.4	1.4	1.4	1.5	.6	2	5	5	4.5	5	7.5	5.5	
	Cold	.5-.6	.5-.6	1.9	1.9	2.0	.9	2.8	6	6	5	5.5	10	7.2	0.6
Overall-Length	inch	2	3-1/8	4-1/2	4-1/2	5-1/4	4-7/8	7	7-1/2	7-1/2	13-3/16	10-3/4	17-1/8	13	3-9/32
Bulb Diam.	inch	1/2	3/8	25/32	25/32	25/32	1	1-1/8	1-1/2	1-1/2	2-1/4	2-7/16	2-13/16	3-3/8	.382
Lamp Oper. Volt.	volts	10-16	10-14	17-23	20-25	15-20	14-20	20-25	29-35	58-72	20-22	45-55	32-36	54-66	16
Lamp Oper. Curr. Nominal	amps	2.7	6.6	7.5	9.0	17.5	30	26.6	28	16	100	50	150	83	5
Ignition Voltage	KV	20-30	20-30	20-30	20-30	20-30	20-30	20-30	20-30	20-30	30	20-30	20-30	20-30	20
Average Brightness	cd mm^{-2}	36	250	96	190	540	4000	250-360	110	150	500	540	700	780	500
Effective Area	mm	.25x.25	.25x.25	.75x1.5	.75x1.5	.5x1	.15x.15	.75x1.5	2x4	3x6	2.5x4	2.5x4	2x4	2.5x4	.25x.50
Average Life	hours	100	100	1000	1000	1000	200	1000	1000	1000	1000	1000	1000	500	
Operates on Hanovia Control #		27800	27800	27800	27800	27801	27801	27801	27801	27801	29912	29912	29912	29912	29011

Lamps which may be operated horizontally are[5] - 914C (Position to be decided at time of manufacture) 919B, 971C, 901B, 901C, 914C, 959C, 970C, 491C, 966C.

TABLE II-c - PEK COMPACT ARC LAMPS

Lamp Type		X 35	(1) X 36	X 75	(1) X 76	(1) PEK 107-2	PEK 110	X 150	(1) X 151	PEK 202	(1) PEK 203	(1) X 300	PEK 500-2	(1)(3) PEK 500-3	(3) X 500	(3) X 1000	(3) X 1600	(3) X 2500	(3)(4) X 5000	(3)(4) X 7500
Fill		Xe	Xe	Xe	Xe	Hg	Hg	Xe	Xe	Hg	Hg	Xe	Hg	Hg	Xe	Xe	Xe	Xe	Xe	Xe
Operating Voltage	volts	12	12	14	14	20	20	20	20	57	57	19	77	77	20	22	24	30	32	33
Operating Current	amps	2.5-3.5	2.5-3.5	4.6-6.2	4.6-6.2	4.2-6.2	4.2-6.2	6.5-8.8	6.5-8.8	3.1-4.0	3.1-4.0	12.5-21.4	5.9-7.1	5.9-7.1	7.5-30	30-54	50-83	58-116	109-203	197-303
Power (rated max.)	watts	35	35	75	75	100	100	150	150	200	200	300	500	500	500 650	1000 1200	1600 2000	2500 3500	5000 6500	7500 10000
Starting Pulse	KV	15	10	20	15	5	10	20	15	10	5	25	10	5	30	30	40	40	50	50
Arc Height	mm	0.3	0.3	0.38	0.38	0.30	0.30	1.0	1.0	1.8	1.8	2.1	4.3	4.3	3.8	3.8	4	6	8	10
Arc Width	mm	0.3	0.3	0.38	0.38	0.30	0.30	1.3	1.3	2.5	2.5	1.7	2.5	2.5	2.0					
Arc Brightness	cd mm^{-2}	400	400	800	800	1,400	1,400	300	300	250	250	350	220	220	350 450	600 750	750 900	650 750	720 950	850 1000
Average Life	hours	200	200	300	300	100	100	500	500	200	200	300	300	300	2000	2000	2000	1500	500	500
Operating Position (2)		90°	90°	90°	90°	90°	90°	30°	30°	0°	0°	30°	0°	0°	30°					
Overall Length	inch	3.375	3.375	3.5	3.5	3.5	3.5	4.75	4.75	4.75	4.75	4.75	6.75	6.75	10.2	12.6	14.5	17.12	21.9	25.5
Bulb Diameter	inch	.375	.375	.50	.50	0.50	0.50	.75	.75	0.687	0.687	.75	1.125	1.125	1.125	1.58	2.1	2.25	2.75	3.2

(1) Has third electrode

(2) Expressed as cone angle about vertical within which operation is permissible.

(3) Requires forced cooling.

(4) Preliminary Specification.

TABLE II D - PEK CAPILLARY HIGH PRESSURE MERCURY ARC LAMPS

Lamp Type		A	B	C	A-46	B-46
Bore	mm	1	1-1/4	1-1/2	2	2
Arc Length	inch	1-1/8	1-1/8	1-1/8	1	1
Brightness	$cd.mm^{-2}$	900	600	400	400	400
Cooling		water	water	water	water	air
Life (Av.)	hours	5	10	60	60	60
Volts	KV	1.75	1.4	1.0	0.9	0.9
Current	amps	1.25	1.1	1.0	1.1	1.1
Power	Kwatts	21	1-1/2	1	1	1

TABLE II-e DATA ON OSRAM COMPACT ARCS

		XBO 75W	HBO 100W/1	HBO 100W/2	XBO 150W/1	HBO 200W (1)	HBO 200W/2	XBO 250W	XBO 450W	HBO 500W (1)	HBO 500W/2	XBO 900W	HBO 1000W	XBO 1600W	XBO 2500W	XBO 6500W	XBF 6000W
Operating Volts	volts	14	20	20	20	65-70	65-50	14	18	85-70	85-70	22		26	30	41	135
Current	amps	5.4	5	5	7.5			18	25			42		63	83	160	45
Power	watts	75	100	100	150	200	200	250	450	500	500	900		1600	2500	6500	6000
Arc Brightness	cd mm^{-2}	400	1700	1700	150	330	330	260	350	300	300	550		650	610	950	3000
Current	amps								30			50		75	95		
Power	watts	85				240	240										
Arc Brightness	cd mm^{-2}								450	580	580	730		800	720		
Useful Range of Regulation	amps					3,1-4			17-30	5.9-7.1	5.9-7.1	30-50		45-75	60-95		
Burning Position (3)		10°	45°	45°	15°	45°	45°	15°	30°	20°	45°	30°		30°	30°	10°	Any
Arc Length	mm	0.5	0.25	0.25	2.2	2.2	2.2	1.7	2.7	4.1	4.1	3.3		4.0	6.0		110
Arc Width (4)	mm	0.25	0.25	0.25	0.5	0.6	0.6	0.7	0.9	1.1	1.1	0,8		1.4	1.5		25
Overall Length	mm	90	90	90	150	128	128	226	260	170	170	325		370	428	510	360
Bulb Dia.	mm		10	10	20	17	17	25	29	28	28	40		52	57	60	
Average Life (5)	hours	400	100	200	1200	200	400	1200	2000	200	400	2000		2000	1500		600
Fill			Hg	Hg	Xe	Hg	Hg	Xe	Xe	Hg	Hg	Xe	Hg	Xe	Xe	Xe	Xe

1) Has starting electrode.

2) Rated values can be maintained throughout life by increasing current from the rated value as emission falls.

3) Cone angle from vertical.

4) Brightness half-width

5) Mean operating time of 2 hours per start.

TABLE II F SYLVANIA COMPACT ARC LAMPS

		HGK 100(1)	HGK 200(1)
Fill		Hg/Ar	Hg/Ar
Operating Volts	volts	20 D.C.	53 D.C.
Operating Current	amps	5	3.8
Power	watts	100	200
Starting Potential	KV	4-20 (A.C.)	0.5-1.0 (D.C.)
Overall Length	inches	3.50	4.25
Bulb Diameter	inches	0.50	0.74
Operating Position(1)		45°	45°
Life	hours	100	200
Arc Length	mm	0.54	2.47
Output	lumens	2,000	9,500

(1) Supplied in three-electrode version also

(2) Expressed as cone angle about vertical within which operation is permissible

TABLE II G WESTINGHOUSE COMPACT LAMPS

		SAH250B (1)	SAHX2500B	SAHX2500C	SAHX3500	SAHX5000 (4)
Lamp Fill		Hg	Hg/Xe	Hg/Xe	Hg/Xe	Hg/Xe
Lamp Power	watts	250	2500	2500	3500	5000
Operating Voltage	volts	42	50	50	56	65
Operating Current	amps	6	50	50	62.5	77.5
Arc Length (Cold)	mm	2.5	6.0	6.0	6.0	7.0
Brightness (Max)	cd/mm^2	250	2050	2050	1450	1200
Output (0 hours)	lumens	10,000	120,000	120,000		
Burning Position (2)		Base down	Anode up	Anode down	Anode down	Anode down
Overall Length (Max)	inches	6-1/4	13	13	13.5	13.5
Operating Vapor Pressure	atm.	30	30	30		
Life (3) (Average)	hours	600	400	400	300	300

(1) Last letter denotes design differences A.C., D.C., Leads, etc.

(2) Lamps may be operated in any position, but operation at an angle exceeding 10° from the vertical will shorten lamp life.

(3) Rated at 8 hours per start.

(4) Requires N_2-gas jet cooling of metal parts.

because the seals overheat. Seal temperatures are set in the range 200-400°C (bulb temperatures around 750°C), depending on the lamp. High power lamps require air jets to cool these seals. Manufacturers had not had direct experience of this but believed the lamps should operate under vacuum if the seals are cooled,[14,16] but with loss in lamp lifetime. JPL has run vacuum tests on a 2.2 Kwatt Hanovia xenon lamp (presumably type 491C) but found that the power had to be reduced;[17] at rated power the life expectancy was drastically reduced and was preceded by total envelope darkening. They found that envelope temperatures did not exceed the manufacturer's limit but that the seals overheated considerably -- the lower electrode seal attained a temperature which was 150°C higher than that for atmospheric operation: Lamp life was 59 hours and ended with catastrophic failure, the reasons for which were not clear at the time (1960).

2.2-2 Brightness distribution

The information one would like to have is brightness contours for different spectral regions. Although manufacturers and users were asked for this information it was unavailable. Consequently only the brightness profiles supplied by the manufacturer and, in some cases, published in the literature can be mentioned. These profiles give the brightness averaged over the photopic response of the human eye.

Figures 2.1, 2.2, 2.4, 2.5 and 2.6 show some of the

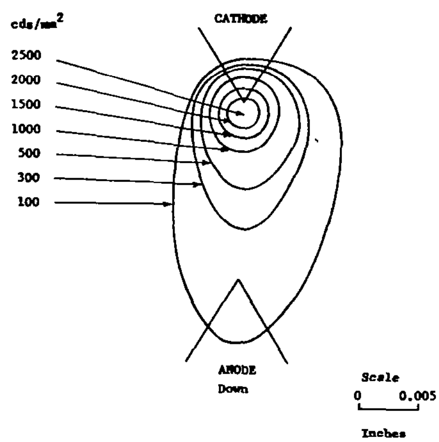


Figure 2.1 Brightness Contours for Hanovia 448C - 80 Watts

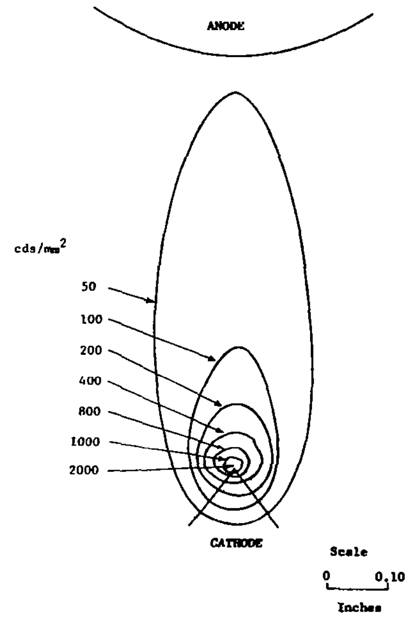


Figure 2.2 Brightness Contours for Hanovia 901/C - Vertical 150 Watts

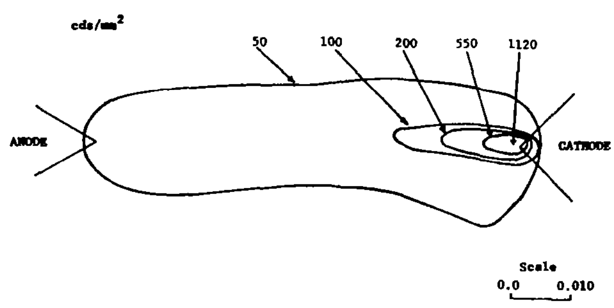


Figure 2.3 Brightness Contours for Hanovia 901/C (Modified Electrodes) Horizontal, 150 Watts

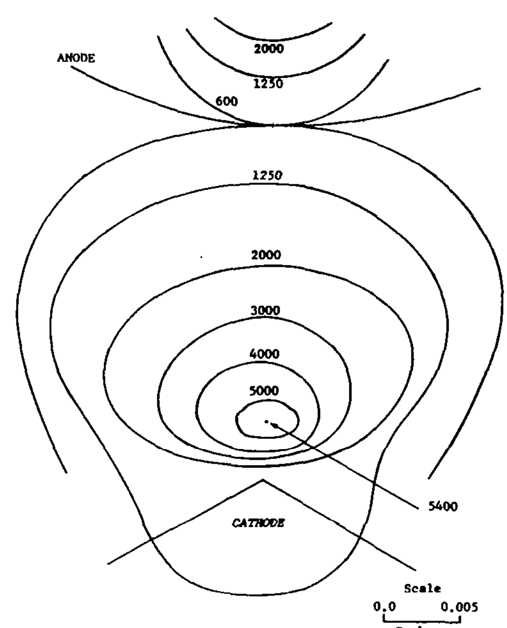


Figure 2.4 Brightness Contours for Hanovia 959C, 500 Watts.

different brightness distributions that can be obtained, differences which must be due, in part at least, to the different electrode configurations. Comparisons between Figures 2.2 and 2.3 show the effect of operating this lamp (with suitably changed electrode) horizontally.

In Figure 2.7 the relative brightness distributions have been plotted for the Osram XBO 900 showing axial and transverse directions. The figure shows a typical case for these arcs but different power levels, dimensions and electrode shapes (in particular) can change this -- see Fig. 2.6. In general, high local brightness is obtained at the expense of uniformity and vice versa. Figure 2.6 shows that, in the brightest region of this lamp, the 5 percent limit of brightness defines a region of approximately 0.15 mm diameter; at position B, however, the 5 percent limit gives a region of about 0.6 mm dia., the brightness ratio for these two cases is 13.

As noted above, the variation of these brightness curves with wavelength appears to have been neither measured nor computed. One would expect the variations to become more pronounced at shorter wavelengths. Lienhard[16] has reported such a variation for the 2.2 Kwatt xenon arc where he found that, in the infrared 800 - 1200 nm the radiance was ten times greater at the maximum, near cathode, than at the minimum which was near the anode. The same ratio was 20 for the photometric brightness. In general, he found that spectra obtained near the center of the arc was

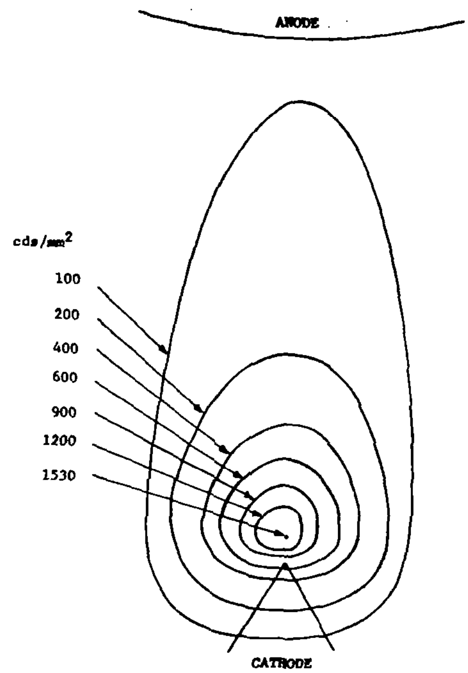


Figure 2.5 Brightness Contours for Hanovia 914C 300 Watts

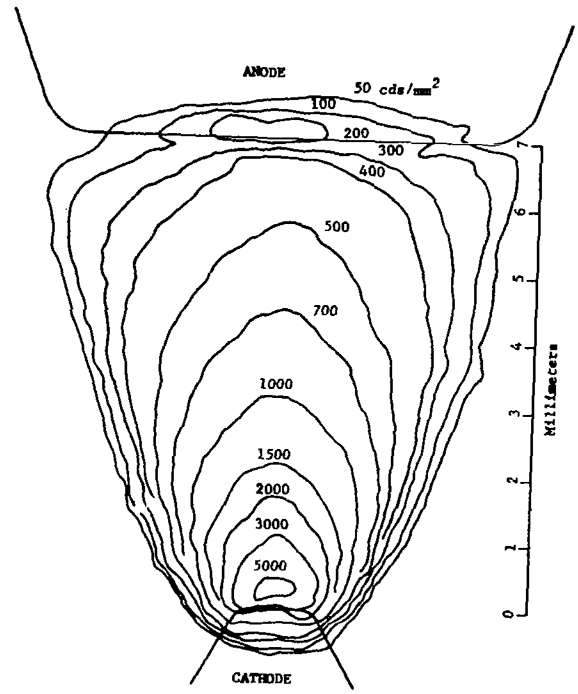


Figure 2.6 Brightness Contours for General Electric XE 5000. 5000 Watts.

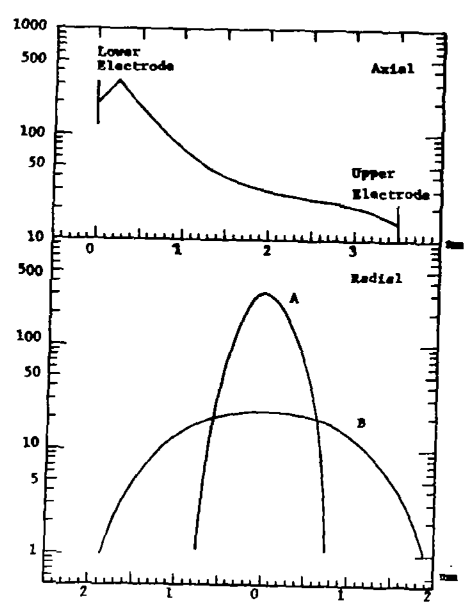


Figure 2.7 Brightness Profiles for Osram XBO 900. 900 Watts.
A. 0.2 cm from lower electrode
B. 3 cm from lower electrode

relatively weaker in the ultraviolet and visible and stronger in the infrared than obtained near the cathode.

The brightness of the arc rises with current but not linearly. In the normal operating current range, a 10 percent increase in current produces a 5 percent increase in brightness.[14] Osram also reports that at very high currents the arc was found to be nearly optically thick and so showed a smaller increase of brightness with current. For xenon arcs operated normally, absorption in the cathode region is around 16 percent, falling to 6 percent at the anode.[14] Thus greater uniformity in the arc is to be expected at longer wavelengths and higher currents.

2.2-3 Angular distribution of intensity

Apart from those arcs having three electrodes, the radiative output is cylindrically symmetric, but variations are found in the plane which includes the lamp axis. These variations are not symmetric, both on account of the non-uniformities in the arc and also because radiant emission from the electrodes is normally present.

Distributions for the Hanovia 959C, 538C and 528B9 are given in Figures 2.8 to 2.10. The distribution curve for the General Electric XE 5000 is shown in Figure 2.11. With the exception of Figure 2.9, all these curves show an increased intensity opposite the anode. For the four figures, the maximum angle over which the output is uniform to within 5 percent is

Fig. 2.8 - Hanovia 959C - 10°

Fig. 2.9 - Hanovia 538C - 15°

Fig. 2.10 - Hanovia 528B9 - 15°

Fig. 2.11 - General Electric XE 5000 - 25°

The specification which was sought was 5 percent over 0.05 steradian, which corresponds to 13° (see Section 6). Hence, such an output uniformity can be achieved. Proper selection of lamp and, possibly, a special design could improve on the above figures.

2.2-4 Spectral distribution of intensity

The data required are values for the spectral steradiancy (watts. $cm.^{-2}$ $sterad.^{-1}$ nm^{-1}), with good spatial resolution, over the emitting region of the lamp. This was not obtained either from manufacturers or from research laboratories but the data supplied by Macbeth Sales Corporation (Osram) came closest. They supplied data sheets giving the spectral steradiancy of four lamps averaged over small areas ranging from 1-2 mm^2. The data obtained, for the lamps given in Table III, are shown in Figures 2.12a and b, which include the spectral transmission characteristics of the water jacket and envelope.

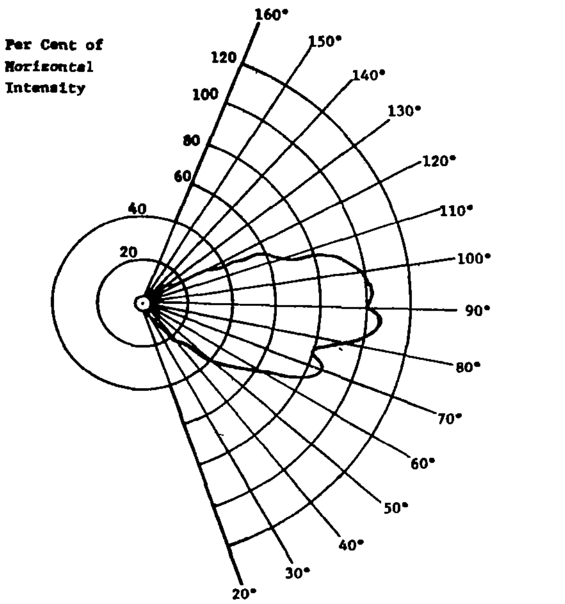


Figure 2.8 Polar Diagram of Emission Intensity for Hanovia 959C 500 Watts.

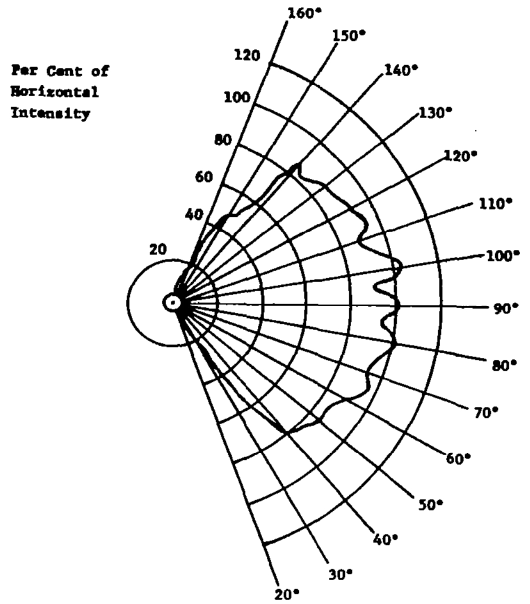


Figure 2.9 Polar Diagram of Emission Intensity for Hanovia 538C, 900 Watts.

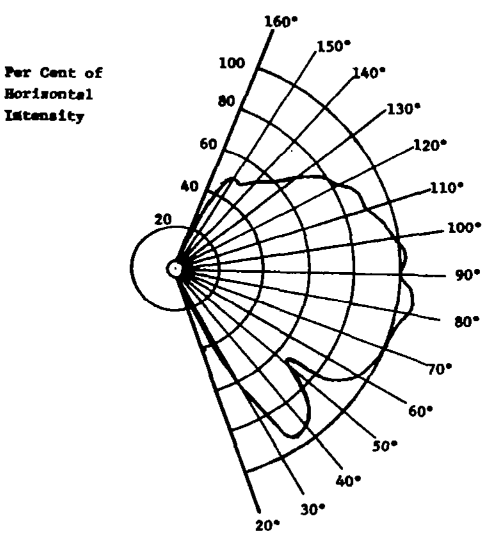


Figure 2.10 Polar Diagram of Emission Intensity for Hanovia 528 B9. 1000 Watt.

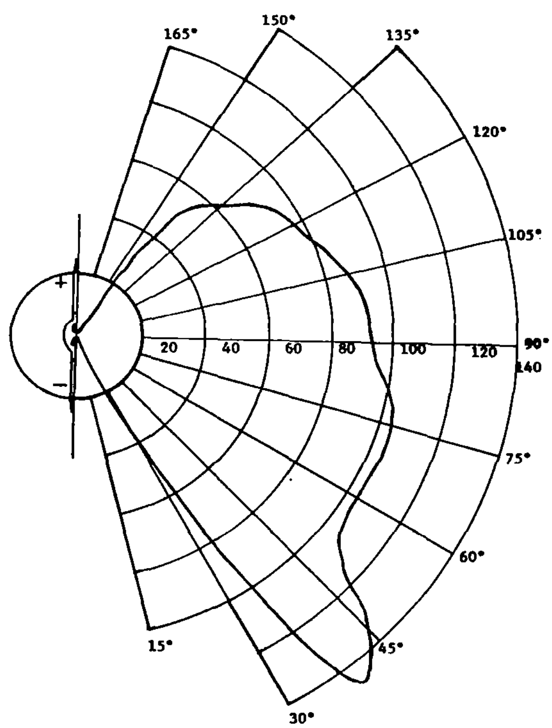


Figure 2.11 Polar Diagram of Emission Intensity For General Electric XE 5000. 5000 Watt

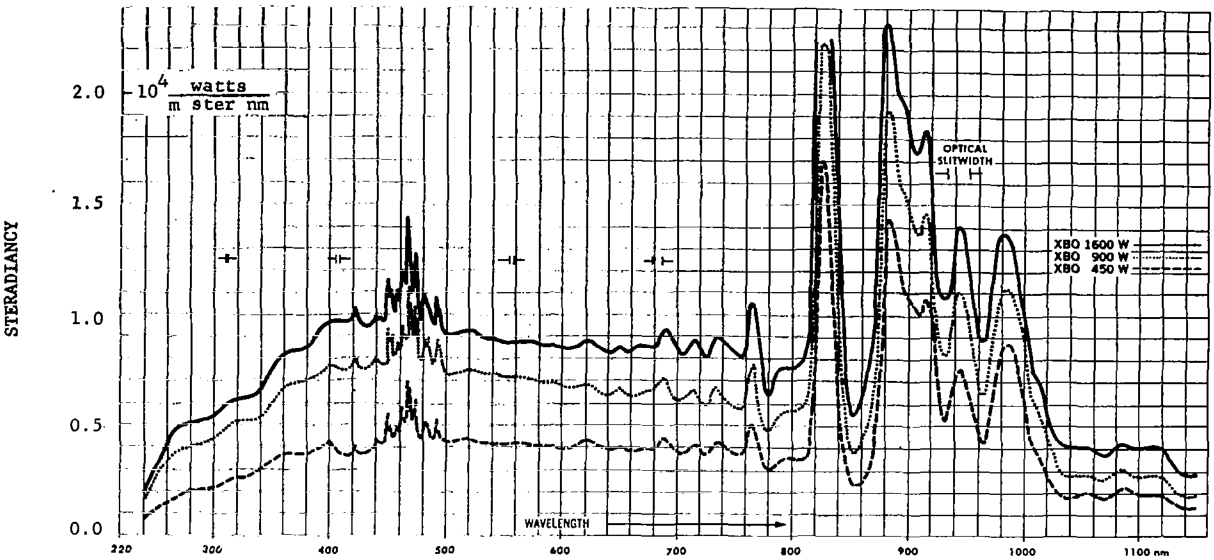
TABLE III

ARC AREAS USED IN SPECTRAL STERADIANCY MEANSUREMENTS-OSRAM LAMPS

Osram Lamp Designation		Area
XBO	450W	2.2 x 0.5 mm
XBO	900W	3.2 x 0.5
XBO	1600W	4.0 x 0.5
XBF	6000W	not given

General Electric, PEK Labs. and Westinghouse (Freeman and Alameda[18]) supplied data for the spectral distribution of energy radiated from the lamp as a whole. Hanovia and Sylvania supplied relative spectral intensities. The Osram data are not as useful as they first appear because the luminous areas in the above arcs are nearly as large as the areas given above, so that Figure 2.12 gives average steradiancies.

The useful wavelength region for compact arc lamps, as dictated by quartz cut-off, is 200 to 2500 nm. Radiation will still be detected to much longer wavelengths, subject to atmospheric transmission, from the hot quartz envelop itself. The low wavelength end can be extended to 170 nm by using a suprasil envelop ——— Hanovia, Osram and PEK all supply such lamps and



"CONDITIONS OF MEASUREMENT"

The curves were obtained using a double-monochromator with a constant slit width, an electron photomultiplier tube and a recording device. The "optical slit widths" as shown on *the drawing increase in size with increasing wavelength due to the reduced dispersion* of the monochromator prisms. The actual or "mechanical slit width" of the five slits indicated was held constant at 0.5 mm during the measurements. The measured area of the arc was imaged on the entrance slit in a 1.1 magnification.

Quartz prisms were used in the monochromator for measurements below 360 nm and also in the infra-red region. Special flint prisms were used for the visible region. The spectral sensitivity of the sensing and recording equipment was normalized by calibrating the instrument with a tungsten-filament lamp.

The particular lamps measured may be considered typical having been selected at random from production lots Each lamp was burned or seasoned, at least two hours prior to measurement and burned in an upright position. The distanee of the lamp from the monochromator was immaterial since the measured arc area was imaged 1:1 on the entrance slit.

The area measured for each lamp was symmetrical about the arc axis and did not include the lamp electrodes. The specific area sizes measured for each lamp area are as follows:

XBO 450 W: 2.2 mm high by 0 5 mm wide

XBO 900 W: 3.2 mm high by 0 5 mm wide

XBO 1600 W: 4 0 mm high by 0.5 mm wide

Room temperature 25°C.

NOTE. When comparing the radiant energy of the lamps at various wavelengths, it should be noted that the integrated values at certain wavelength intervals must be considered rather than absolute values at distinct wavelengths. An approximation of the minimum value of the wavelength interval may be obtained by using twice the value of the "optical slit width" indicated on the drawing for a given region.

Figure 2.12(a) Horizontal Spectral Intensity Distribution in Osram Xenon Compact Arcs

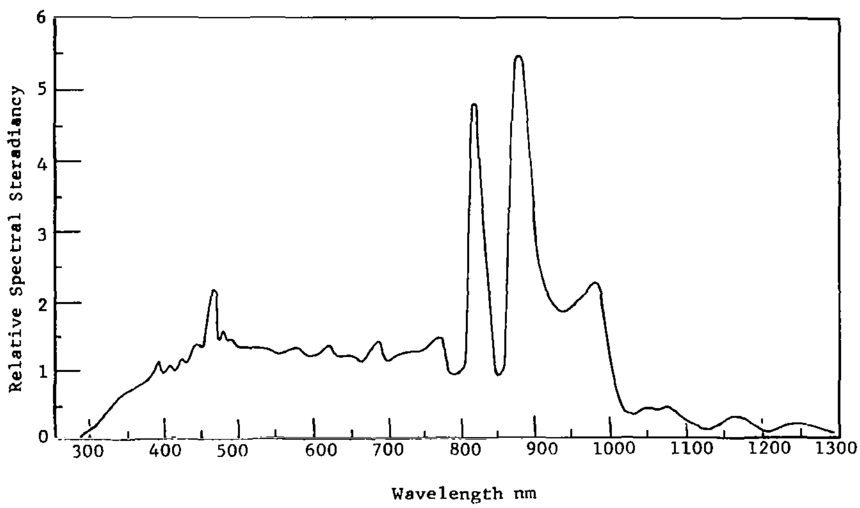


Figure 2.12(b) Relative Spectral Intensity of Osram XBF 6000 - Xenon Capillary Arc.

the other companies may also.

Interest in solar simulation has stimulated efforts to measure the radiant properties of these lamps. Internal reports were obtained from two such laboratories, JPL and NASA Goddard Space Flight Center, giving details of their measurements. Solar simulation requires the matching of the Sun's irradiance at the Earth, and lamp measurements for this purpose do not normally give the spectral steradiance as defined above. However, the measurements made by these workers are amongst the most accurate available and should be mentioned.

Laue[22] gives irradiance measurements made for JPL by the Eppley Laboratory Inc., on Hanovia xenon and mercury-xenon lamps (he does not specify type but presumably they were in the 2 to 5 Kwatt range) and compares them with other lamps - see Section 2.2-8 More detailed work on commercial lamps is reported by Duncan, Hobbs and Pai.[23] These authors report steradiancy measurements in the D.C. compact arc lamps listed in Table IV (as well as on some A.C. lamps).

TABLE IV

D.C. ARC LAMPS STUDIED BY DUNCAN et al.[23]

Manufacturer	No.	Type	Power (watts)
Osram	XBO2001	Xenon	1600
Hanovia	929B	Hg-Xe	2500
Hanovia	418C	Xenon	800
General Electric		Xenon	2000

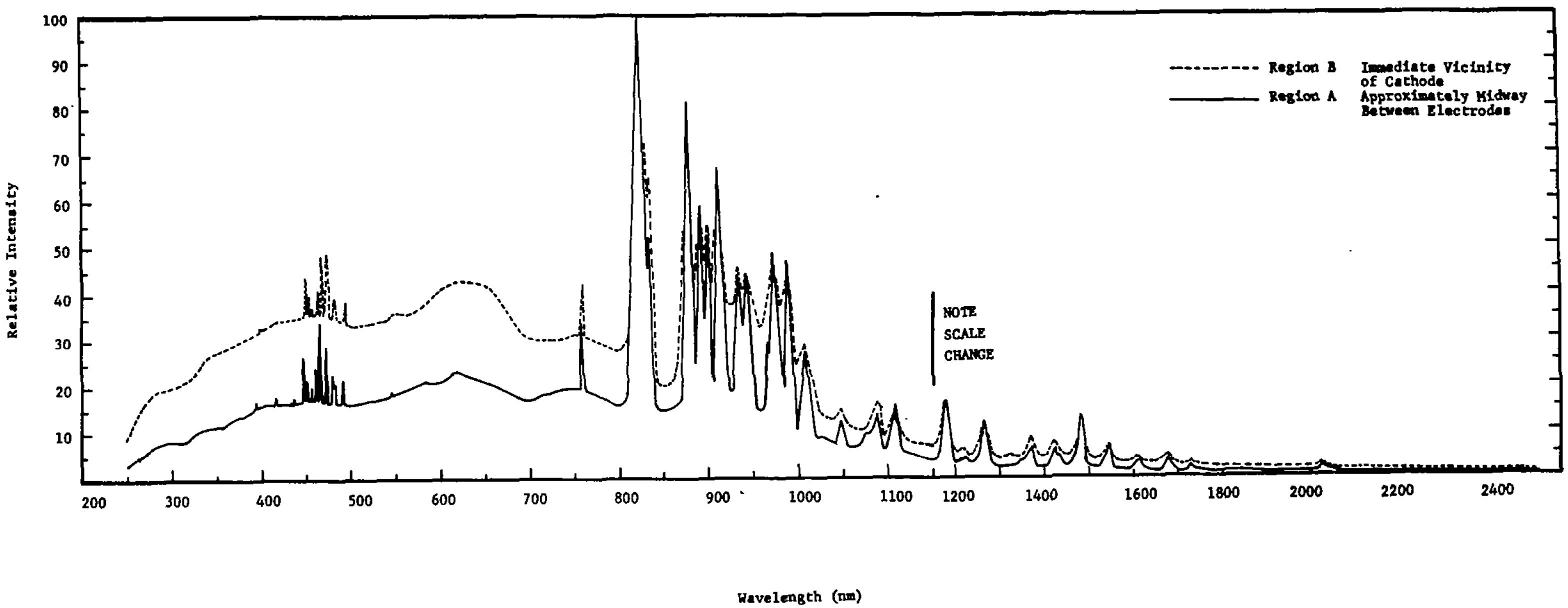


Figure 2.13 Relative Spectral Intensity for Hanovia 2,500 Watt Xenon Lamp

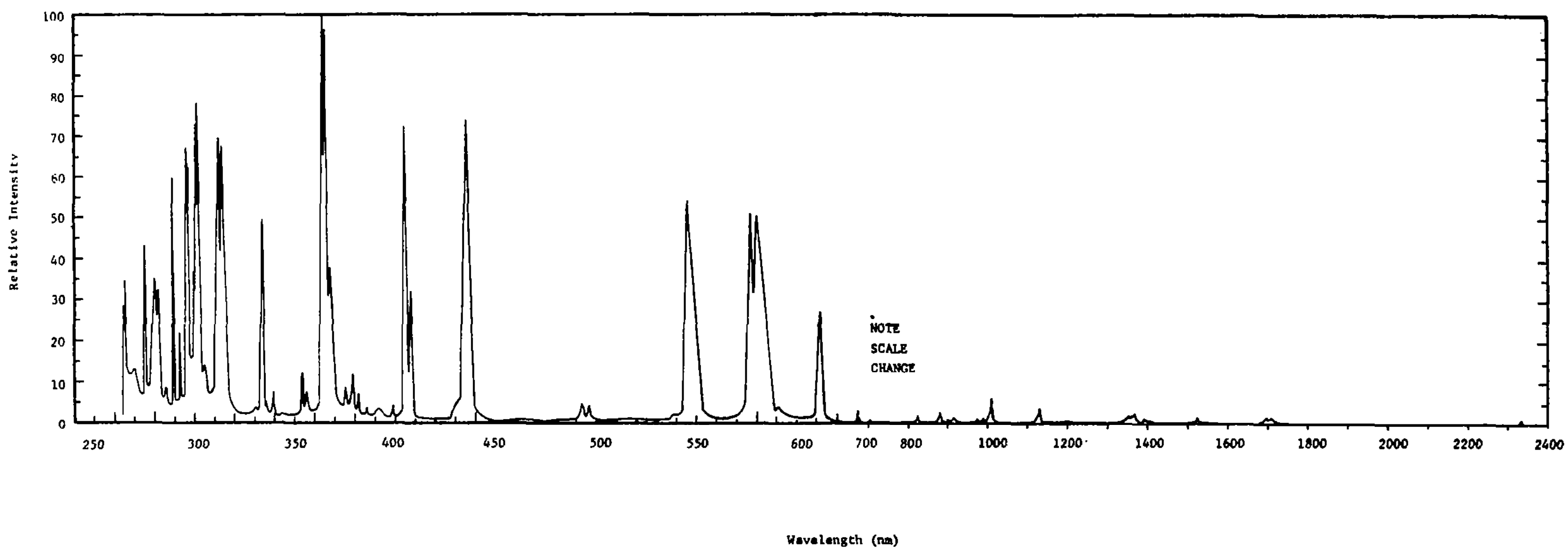


Figure 2.14 Relative Spectral Intensity for Hanovia 2,200 Watt Mercury-Xenon Lamp.
Differences Between Regions A and B are Negligible.

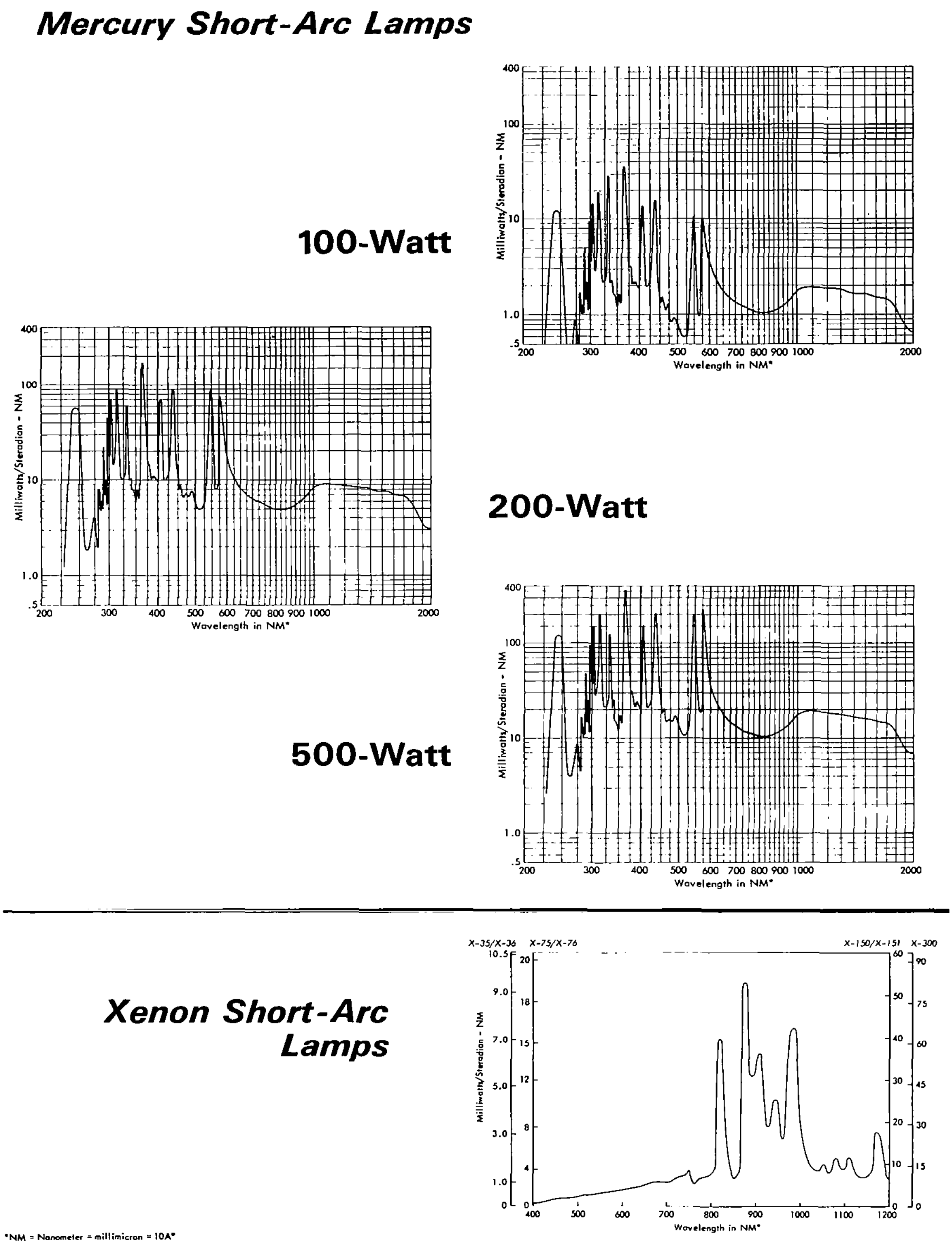


Figure 2.15 Spectral Energy Density for PEK Lamps

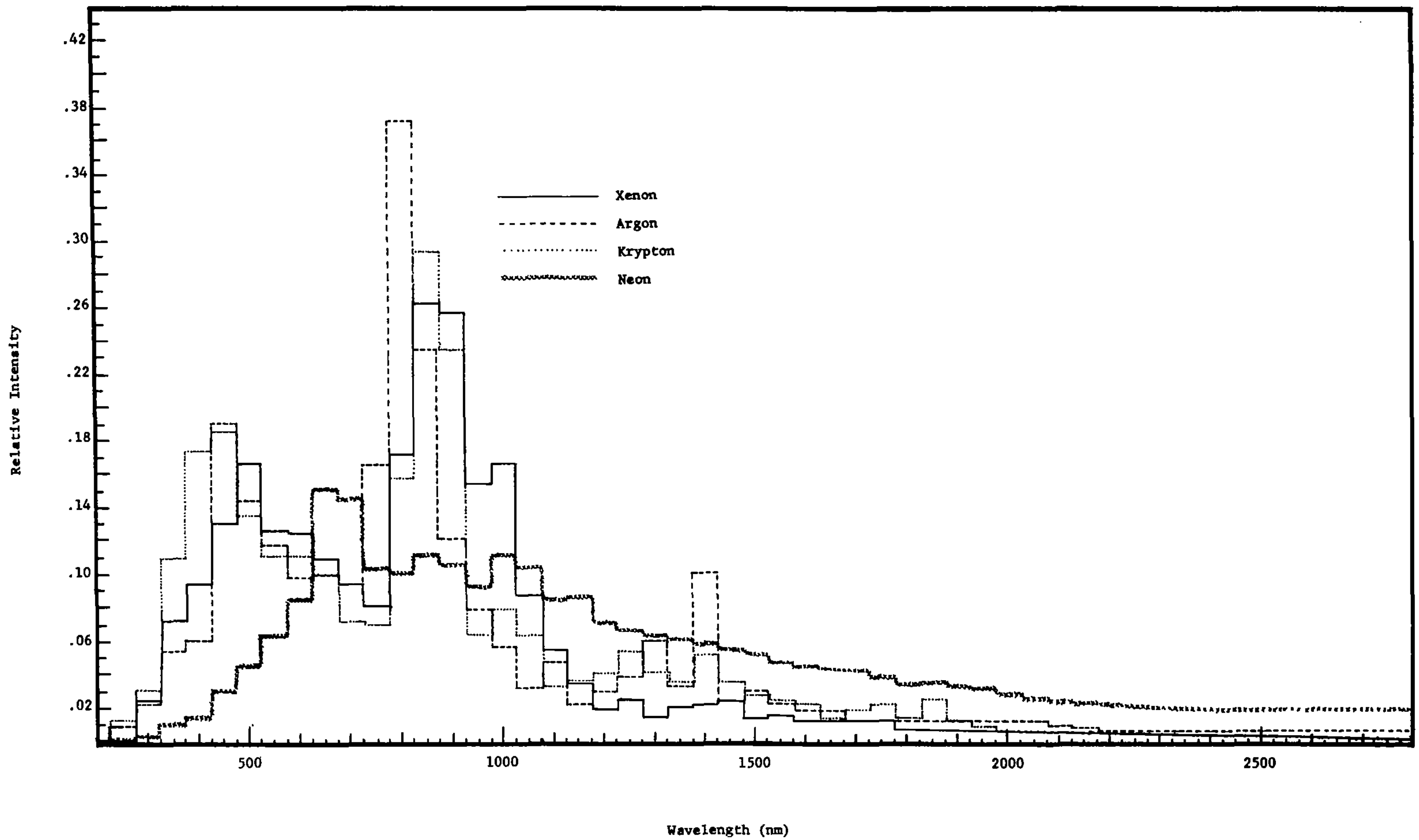


Figure 2.16 Comparative Intensity Curves for Rare Gas Compact Arc Lamps [22]

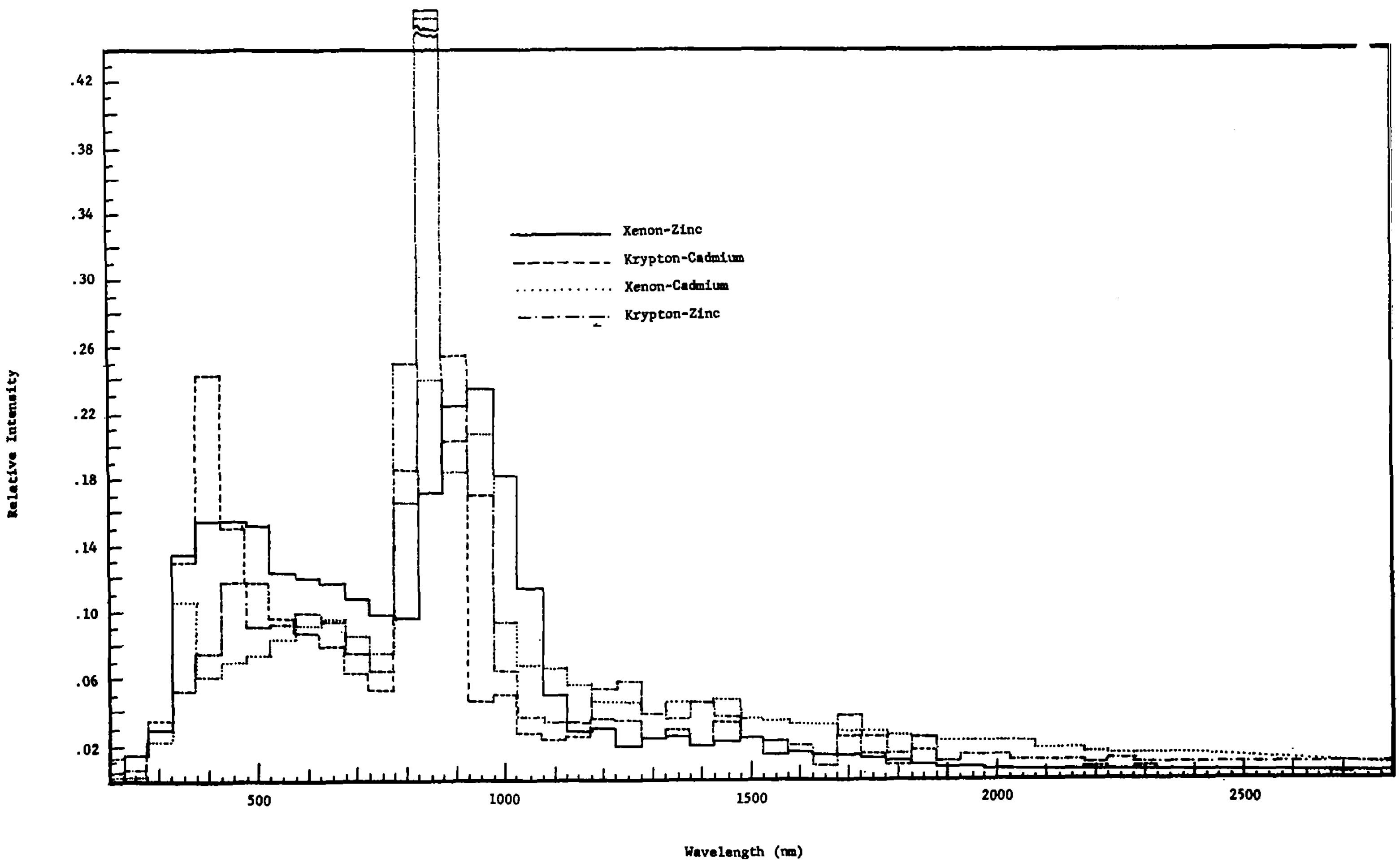


Figure 2.17 Comparative Intensity Curves for Rare Gas Compact Arcs Containing Zinc or Cadmium [22]

The measurements were made over a range of power levels above and below the rated values. One conclusion of this work was that the spectral distribution was relatively insensitive to the operating power level of a lamp, which is in agreement with Lienhard[16] and Breeding.[20]

The Eppley Laboratory Inc. made measurements on the relative spectral intensity distribution on several lamps for Engelhard Hanovia Inc., who supplied a copy of their report. Measurements were made on new and old (age not specified) Hanovia lamps in two regions.

A. Approximately midway between the electrodes.

B. In the immediate vicinity of the cathode.

These were done for 2.5 Kwatt xenon and 2.2 Kwatt mercury-xenon lamps. The results for the new lamps are shown in Figures 2.13 and 2.14. The effect of age appeared to be slight, some changes in the relative intensities of the mercury lines, in the mercury-xenon lamp, and some suppression of the continuum in the xenon lamp.

The spectral energy distribution of the PEK lamps is shown in Figure 2.15, reproduced from the PEK literature. The method of measurement was not given but, assuming the radiation was from the whole lamp and taking an average area according to Table IIC, the spectral steradiancies are obtained.

2.2-5 Lifetime

Lifetimes have been listed in Tables II A to G. As is also noted in the tables, this lifetime is strongly dependent on the number of starts the lamp experiences. The times quoted usually give a fall in radiative output by 20-30 percent. This decrease is chiefly due to the deposit of electrode material on the lamp envelope. The resulting increased absorption by the envelope can cause overheating and rupture.

The effect of operating lamps in vacua and at higher power levels was described in Section 2.1. Both these conditions drastically shorten the lifetime of compact arcs.

The Jones and Lamson Machine Company,[24] Springfield, Vermont, which makes power supplies for the Westinghouse SAH 250B lamp, but also suitable for Osram, PEK and Sylvania 200 watt mercury lamps, state that they have occasionally obtained useful lifetimes up to 10,000 hours (cf. Table II (G) which gives 600).

2.2-6 Stability

Good stability is of great importance in any optical system in which radiation is received from only a small region of the arc.

Stability covers fluctuations in the arc emission intensity and also arc movement. Furthermore, in many instances it is important to know whether the arc re-strikes at the same location on the electrodes.

a) Power Supply Ripple

This is not a serious problem as additional smoothing can be introduced as required. PEK power supplies have 3% ripple. This can be reduced to 0.1% but the arc instabilities exceed this.[25]

Power supplies for compact arc lamps are made by many different manufacturers but these were not generally consulted during this survey, lamp manufacturers will supply the names of these. One manufacturer may be quoted: Christie Electric Corporation, which makes power supplies for all types of compact arc lamps, specify current regulation of $\pm$ 1% and ripple of 1% (rms) or less.

Hanovia power supplies are quoted as having a current regulation of $\pm$ 1% (to $\pm$ 10% change in line voltage) with ripple of 1-3% (rms); this increases with current, they also supply filter kits for additional smoothing if required. Both Lienhard[16] and Osram[14] state that the fluctuation in lamp radiation intensity shows about the same amplitude as the current ripple. However, Howerton[26] (American Instrument Co. Inc.) reports that a 4% ripple from the power was smoothed to approximately 1/2% in the lamp output.

b) Intensity Fluctuations and Arc Movement

Not much information was obtained on this topic. The Hanovia 901 C is relatively stable with short period fluctuations less than 2%.[16] The American Instrument Co. Inc.,[26] which is a larg user of Hanovia lamps, supplied the following data on xenon arc stability:

i) Fluctuations over a period of 15 minutes, ± 14%

ii)	Drift	8 hour period	10%
		several days	20%
		several weeks	30%
		several months	50% to the usable life

of approximately 1000 hours.

Howerton had no data on mercury arcs but indicated that they were more stable.

Lienhard[16] reports that most of the Hanovia lamps exhibit very little arc movement. An exception is the 959 C, a very short arc. In this case the arc sometime jumps from one location on the cathode to another, possibly 0.015 inch away. This lamp is fairly stable for the first few hours of operation but the arc may then move.

Another type of instability was mentioned by Lienhard,[16] although the arc remains in one spot, it can pulsate. The arc expands or contracts radially, but the radiative output is stable.

The Eppley Laboratory also reported xenon arc instabilities;[27] both rapid oscillations in intensity and jumps between discrete intensity levels were observed. It seems that the latter may not have been due to arc movement. An interesting study of this problem has been made by Budde[28] and reference should be made to his article by anyone concerned about xenon arc stability. Budde conducted two types of experiments. In one the arc was imaged on a slit, with the detector behind, so that arc movement is detected along with intensity fluctuations. In the other there was no slit, so that only intensity fluctuations were detected. He studied both new and old (age between 200 and 300 hours) Osram XBO 501 DC xenon arc lamps. The aged lamp showed somewhat better stability. Up to 100 hours life, the lamp showed drifts of $\pm$ 10% in intensity in five minutes; initially there was a ripple of about the same magnitude superimposed, this fell to $\pm$ 0.5% after the first 100 hours. Measurements made behind the slit, in the first 100 hours of life, showed fluctuations of up to $\pm$ 40% per 10 minutes ($\pm$ 10% in a few seconds) and a ripple of 2%. These figures improved somewhat for the aged lamps where the best results were obtained after 90 minutes of operation (in addition to lamp age of 200-300 hours), giving a drift of less than 1% and ripple of 0.5% in 20 minutes behind the slit.

Redfield[29] has described a system for improving the stability of light output from a xenon arc. This system adjusts the curren supplied to the arc in order to maintain the detected light intensity constant. He has obtained successful operation with a 175 watt arc, reducing a 1 to 2% instability down to 0.1%.

Wasserman[30] has found that the Hanovia 901C gives good stability. He made four types of measurements: no aperture, an aperture centered on the cool part of arc, aperture centered on the hot spot and an aperture centered on the lateral edge of the hot spot. The first three conditions gave drifts of one percent an hour, the last gave 4 percent per hour. He also found that the arc re-struck at slightly different places on each ignition. "Flares" occurred infrequently, these were sudden bursts of higher intensity.

Lanzo[31] has used a 900 watt compact xenon arc (Hanovia) and, when viewing the whole arc, found the intensity constant to within ± 1% over a one-hour period. However, he did find fluctuations in spectral intensities: at 665 nm these were about ± 5% but could be ± 10% for short periods.

Both Lienhard and Howerton report that the arc may re-strike at different locations. The effect occurs for both electrodes but is greatest for the lower (conical cathode) as the arc may move to re-attach on a different side, the effect is random.

Osram[14] reports somewhat differently. They find that the cathode spot does not wander about except in faulty lamps or lamps which have been operated on reverse polarity at some time. Near the anode small fluctuations (insignificant according to Osram) are observed and may be periodic of low frequency, these could be the same as the fluctuations observed by Lienhard[16] and Budde[28] (about 5 cycles/min). Osram also states that the arc usually re-strikes at the same cathode spot and good stability is not achieved until after a few minutes of operation. Arcs were less stable when operated horizontally.

These different reports may, of course, be due to different observing conditions but could also be due to lamp differences, possibly operating pressures or power levels. It does appear, however, that the mercury or mercury-xenon lamps are more stable, although these have been studied less.

PEK Labs. supplied a paper by Buckley and Gerue[33] which mentioned such instabilities, indicating that these were caused, in part at least, by convective flow variations inside the lamp which, in turn, were caused by changes in the cooling of the quartz envelope. Careful electrode design could reduce arc wander.

2.2-7 Effect of an acoustic environment

There may be applications in which these sources have to operate relatively near rocket exhausts or in other high acoustic environments. The only data obtained as to how such lamps behave under these conditions were from Lanzo[31] who operated a 900 watt xenon arc within one foot of a Thermal Dynamics 60 Kwatt plasma torch, which produces a high intensity sound over a wide spectrum and up to 120 db. Lanzo found no appreciable effect on the lamp.

Buckley and Gerue[33,34] mention acoustic resonances that can be set up inside compact arcs, with the envelope acting as a resonant cavity. They were concerned with the problem of arc modulation, where these resonances were difficult to avoid and could extinguish the arc. The frequency of these resonances is proportional to pressure and inversely proportional to the bulb diameter. No evidence has been obtained to show that an arc subjected to an external acoustic load would excite these resonances but it seems possible. Table V shows some values given by these authors.

TABLE V SOME FIRST MAJOR RESONANCES
IN Xe COMPACT ARC LAMPS

Lamp Power	Frequency
75 watts	50 kc/s
100	30
250	11
350	8
450	6
1500	3

Neither Osram nor Hanovia was able to comment on this question.

2.2-8 Special Lamps

The lamps marketed commercially are filled with xenon, mercury or a combination (mercury-xenon or mercury-argon). PEK Labs. has supplied 500 watt lamps with suprasil envelopes filled with Krypton to Dr. Norman Simmons[98] of the University of California. These were intended for use in the ultraviolet. Simmons operated these at wavelengths down to 185 nm and found the Krypton lamps worked well, gave good stability and an intensity 2 to 3 times greater than the Osram 450 watt arc in the ultraviolet, but about the same in the visible. This may have been primarily the effect of the suprasil envelope but the advantage of krypton was the much lower infrared emission compared with xenon. Simmons had operated the krypton lamp at 750 Watts for over 300 hours and believed higher powers could be used.

Some interesting lamps have been made by Hanovia for JPL and data on these were kindly furnished by Dr. Laue*. The object of testing these lamps was to obtain a better spectral match to the Solar curve. The types of lamps tested were as follows:

i) Xe, Xe-Zn, Xe-Cd, Hg-Xe-Zn, Hg-Xe-Cd.

ii) Kr, Kr-Zn, Kr-Cd, Hg-Kr-Zn, Hg-Kr-Cd.

iii) Ar

iv) Ne

v) Hg-Xe with variable mercury vapor pressure

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* The work reported in references (17) and (22) represents one phase of research carried out at the Jet Propulsion Laboratory for NASA under contract NAS 7-100. Material is reproduced here by permission of Mr. James G. Jackson Jr., Technical Information Section, Distribution and Control Group.

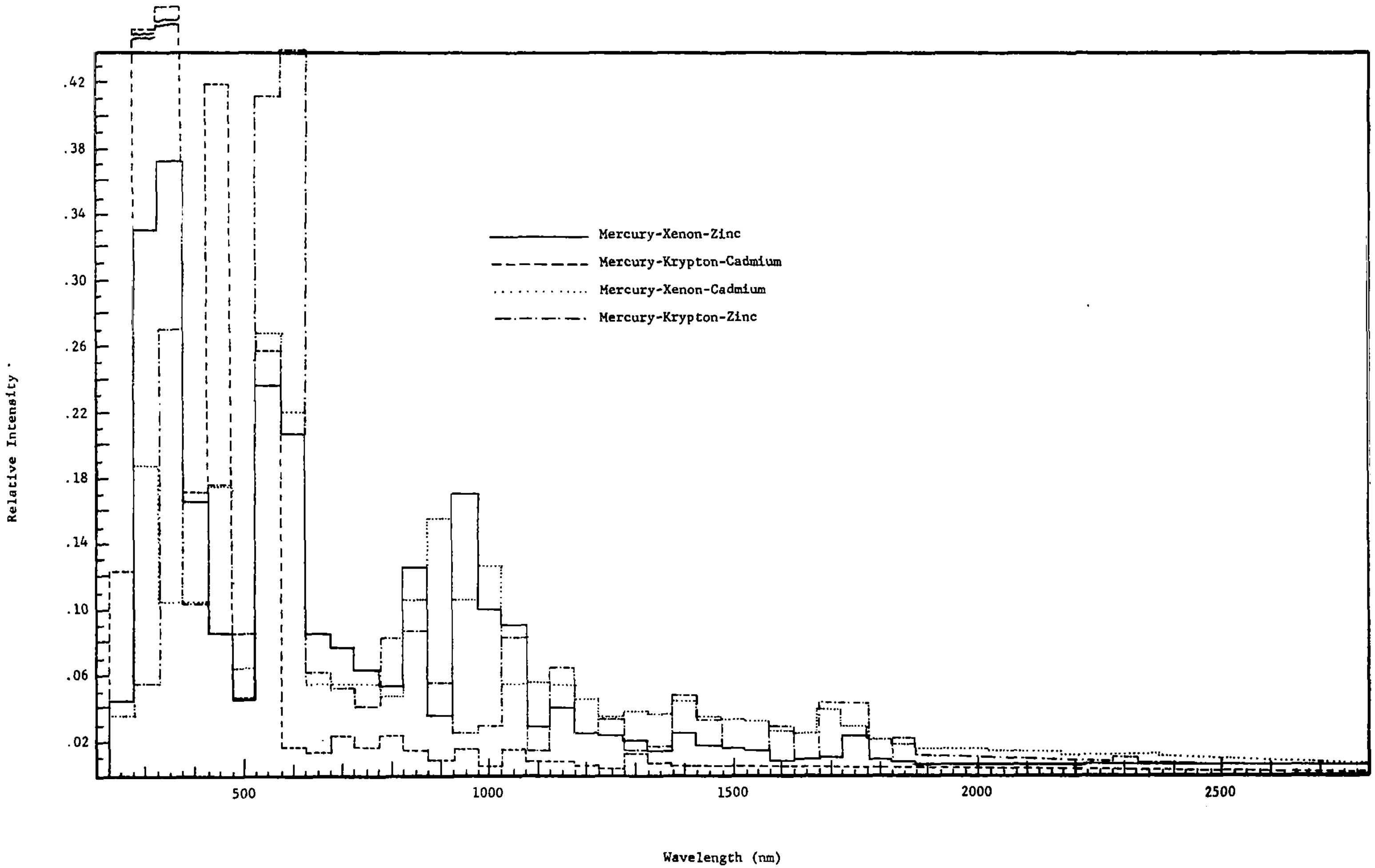

Figure 2.18 Comparative Intensity Curves for Mercury-Rare Gas Compact Arcs Containing Zinc or Cadmium [22]

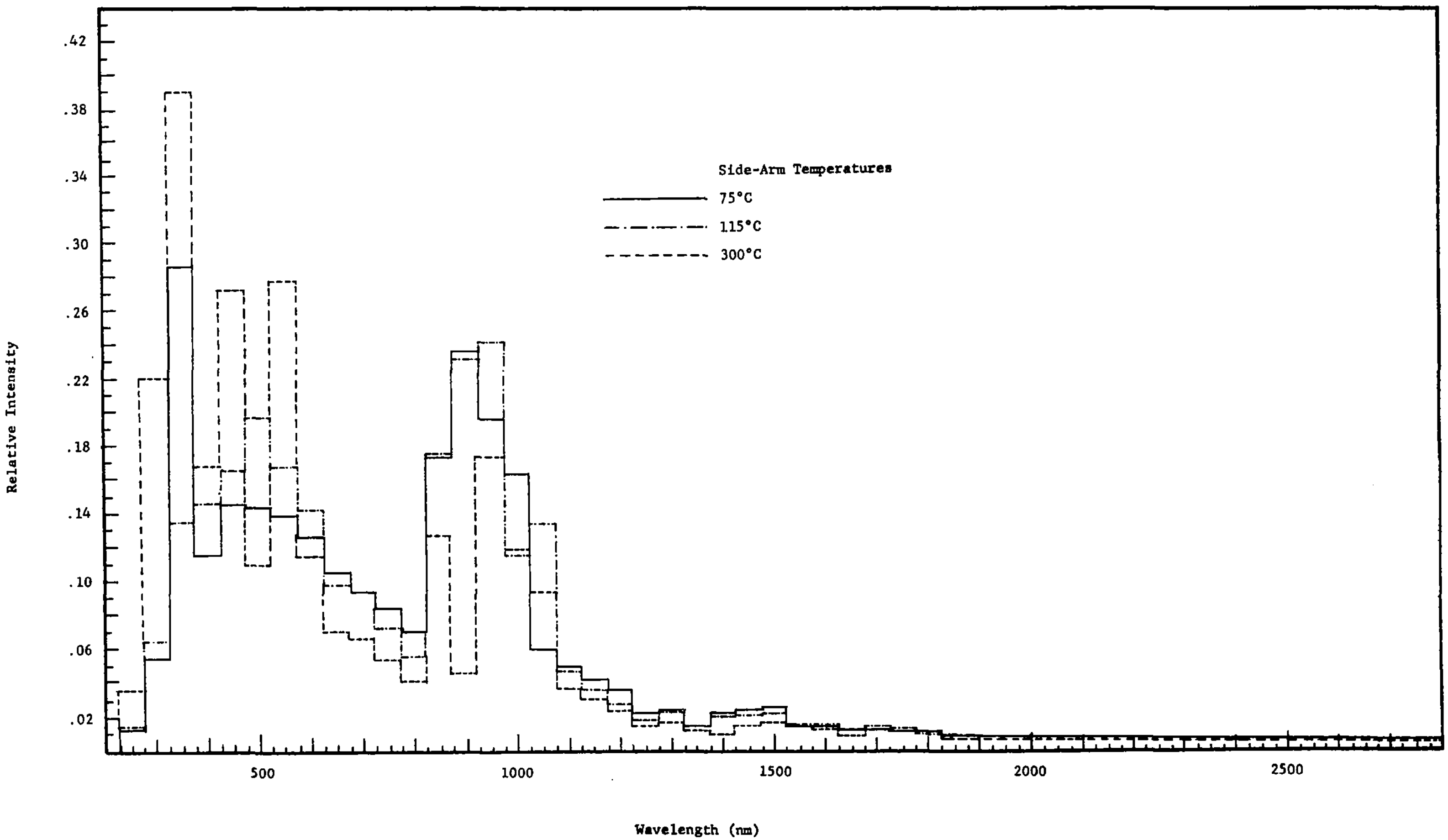

Figure 2.19 Comparative Intensity Curves for Mercury Compact Arcs Operated at Different Partial Pressures of Mercury Vapor [22]

Lamps with alkali metal additives were also tried but it was found that the alkali metal reacted strongly with the heated quartz envelop, giving a very short life.[22] The lamp listed under (v) had a stem attached which could be temperature controlled, thus varying the partial pressure of mercury vapor. Figures 2.16 to 2.19 were re-drawn from reference (22), where the data were recorded with a 10 nm pass band. Lane gives the spectral irradiance from these lamps under his experimental conditions.

Larson, Fraser, Cushing and Unglert[35] reported adding thallium, in the form of thallium iodide, to mercury arc lamps. This had the effect of greatly increasing the relative output at 530 nm, giving a much increased luminous efficiency. This introduces the emission lines of thallium and possibly iodine also (only thallium was mentioned in the paper).

2.3 CARBON ARCS

The carbon arc consists of a discharge between two carbon electrodes in the air usually at atmospheric pressure. The electrodes are carbon or graphite -- usually with additives -- and are consumed during operation. An automatic feed mechanism is used to maintain a constant arc gap. During operation a crater depression is formed at the tip of the anode and this is viewed for the brightest source. The gases in the arc stream are even hotter than the positive crater but have a much lower emissivity. Gas emissivity can be raised, however, by adding compounds to the carbon rods; these volatilize and emit strongly, giving a bright arc flame. Thus, the relative spectral distribution of intensity from the arc can be influenced by using different additive materials to the carbon or graphite rods. At high current densities the anode spot spreads over the entire tip of the anode and leads to rapid evaporation: with suitable additives to the electrodes such an arc produces a very intense flame -- this is called the Beck arc.[8]

The temperature of the arc depends on the radiation conditions. A strongly radiating arc tends to be cooler, thus a 200 ampere Beck arc has a temperature of 6000-7000°K in the anode flame whilst a carbon arc at the same current with a scarcely luminous flame attains temperatures of 11,000-12,000°K in the anode region.[8] The temperature of the carbon crater is lower. Finkelnburg and Latil[36] report on a high intensity carbon arc, operating at 200 amperes, which automatically replaces the carbon rods as required, thus giving a longer operating time. From the measured brightness the authors deduced an equivalent blackbody temperature of 5400°K for the positive crater, although the relative spectral energy distribution gave a temperature of 7000°K. The absolute temperature of the crater was a little larger. This arc had a highly luminous flame which emitted more than 50 percent of the total radiation output of the arc.

The low current carbon arc has a lower temperature.

MacPherson found the positive crater to radiate at a brightness temperature of about 3840°K.[37] Similar results have been reported by Null and Lozier.[38]

The spectral distribution of the emitted radiation depends on the region of the arc viewed, power dissipation, and nature of the carbons. From what has been said already it is clear that the anode flame is strongly influenced by the nature of the carbons, especially in the high current arc; even when viewing the positive crater, the strength of the radiation from the anode flame can be sufficient to appreciably modify the spectral energy distribution. Data on the spectral emission characteristics of the various types of carbons can be obtained from the National Carbon Company: Koller has summarized this in his book[5] and reproduces several curves. The most noticeable feature is the strong emission from the CN violet bands at a wavelength of 388 nm; the different carbons cause most changes below 500 nm but appreciably enhanced emission around 700 nm is obtained with strontium cored carbons (National E).

Commercial arcs are available in various sizes from small laboratory sources to high power arcs used for special lighting requirements and suitable for solar simulation. The study of manufacturers' literature on this type of source was far from complete, primarily because of the time spent on other types of sources in this survey. However, the data that were obtained are considered adequate to allow an assessment of the qualities of the low-current carbon arc source for comparison with other sources that are available.

Carbon arcs may be obtained from

Genarco, Inc., Jamaica, New York

Mole-Richardson Co., Hollywood, California

The Strong Electric Corp., Toledo, Ohio

Carbon arcs for use as laboratory illuminators are supplied by, for example,

Bausch and Lomb Inc., Rochester, N.Y.

Klinger Scientific Apparatus Corp., Jamaica, N.Y.

Spectroscopic source units can be obtained from many of the manufacturers of spectroscopic equipment, but they do not appear to have any special application in the type of work for which this survey was conducted.

In 1940 MacPherson published a paper[37] describing the properties of the low current carbon arc and indicating its suitability as a radiation standard, with an intensity much greater than the tungsten lamp. More recently Null and Lozier have published work on the same theme.[38] In their paper these authors review the work that has been done on the carbon arc and the uncertainties and discrepancies which exist. They also establish a set of conditions for optimum operation (the arc was operated in the range 8-18 amps., 60-71 volts); Olsen reports complete agreement with these procedures.[46] Subsequently, the Mole-Richardson Company placed on the market their Molarc Lamp Type 2371 based on the conditions established by Null and Lozier. The Molarc operates at 9-18 amperes D.C. and 63-70 volts. It can be supplied with different diameter carbons which affect its performance as described below. Duncan, Hobbs and Pai[23] have measured the spectral irradiance from three different carbon arcs manufactured by the Strong Electric Co., and Alexander[39] has studied the Genarco ME 4CWM carbon arc.

The value of the carbon arc lies in the uniformity of output from the positive crater and the high emissivity that is achieved. Null and Lozier review the measurements made by other workers and find substantial agreement with their own result, that the positive crater radiance follows that of a blackbody at 3800°K, (with spectral emissivity of the crater between 0.96 and 0.98) in the spectral range 400 to 4200 nm; these authors distrusted their results beyond 4200 nm. MacPherson's results[37] were substantially the same as Null's and Lozier's and showed the strong CN violet emission, see Figure 2.20; at low wavelengths MacPherson found a resumption of the blackbody radiation curve but for a temperature of 3990°K.

The spectral radiance of the low-current carbon arc has been measured by Johnson,[40] using the same type of arc as MacPherson. Johnson's results are shown in Figure 2.20b they were obtained by viewing through 120 cm of air and exhibit the sharp cut-off due to air below 190 nm. Some of the features between 190 and 200 nm may be due to oxygen absorption (e.g. the 5,0 band at 190.2 nm). The high radiances at 193.1 nm and 247.8 nm are due to carbon lines. In the figures the solid line represents radiation from the arc stream as well as from the incandescent anode. The broken line is for radiation from the arc stream only (viewed 1 mm in front of the anode) and shows that this is the major contributor at these wavelengths. Consequently, as a light source for this region the anode flame could be viewed alone, thus reducing the contribution from scattered radiation in a monochromator detecting system.

Hattenburg has measured the spectral radiance of the Mole-Richardson arc over the spectral range 210-850 nm[122]. The measurements were made with a high accuracy spectroradiometer developed at NBS and the estimated errors are between 1.5 and 5 percent. Hattenburg's results show a continuum emission which is close to blackbody emission for a temperature of 3792°K: the deviation is $< \pm 0.5\%$ at 550 nm, $\pm 1.5\%$ at 430 nm, around $\pm 2\%$ at 300 nm. Superimposed on this continuum is considerable emission from line and band spectra, specially at lower wavelengths: the spectra were recorded with band passes of 2 to 5 Å.

Emission intensity data for wavelengths longer than 420 nm were reported by Rupert and Strong,[41] who compared the relative intensities of the carbon arc and a Globar, operated at 1175°K. The arc was very much stronger out to 500 nm and then was approxi-

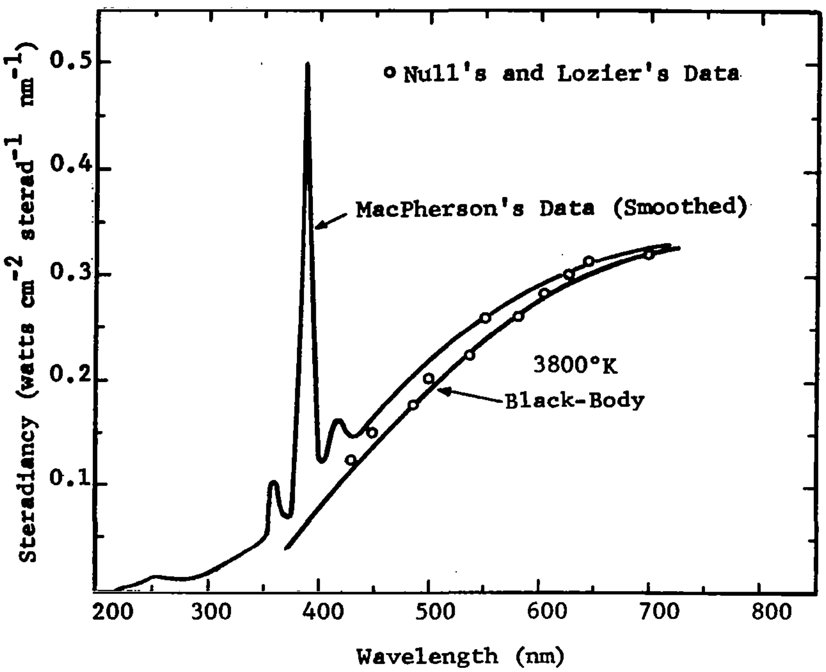

Figure 2.20(a) Spectral Steradiancy of Low Current Carbon Arc in the Visible

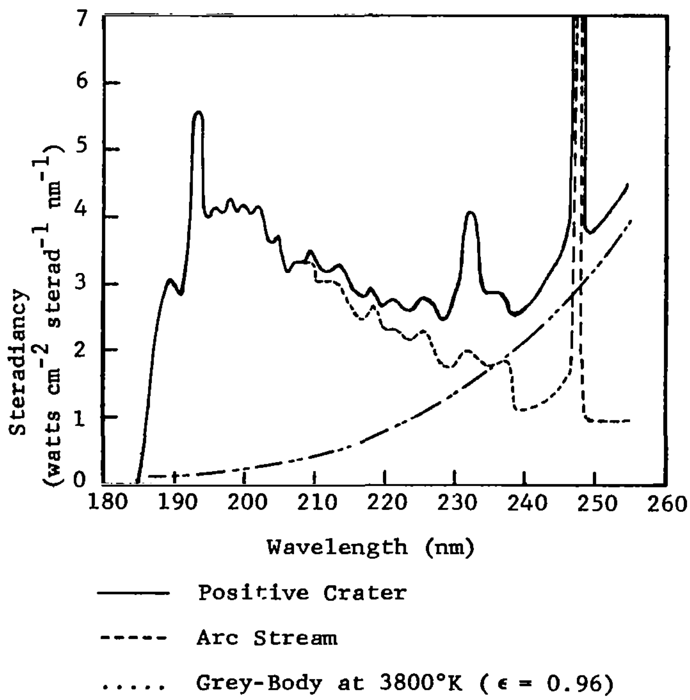

Figure 2.20(b) Spectral Steradiancy of Low Current Carbon Arc in the Ultraviolet[40]

mately 6 to 8 times more intense out to 15,000 nm see Figure 5.3.

The relative spectral intensity distribution obtained with the Bausch and Lomb microscope illuminator arc is shown in Figure 2.21 for a current of 5.5 amps D.C. and 5.6 mm carbons (National L8500, copper coated).

Figure 2.22 is the brightness distribution across the crater in the low-current carbon arc,[38] using graphite rods (the brightness was measured in photometric units). Null and Lozier obtained similar results with carbon rods, but it was found easier to maintain the arc current for maximum radiance when using graphite.

The brightness distribution across the positive crater for a high current carbon arc is shown in Figure 2.23, from Finkelnburg and Latil.[36]

Measurements on beam uniformity were made by Alexander,[39] for the Genarco arc, Model ME4CWM, at a distance of 64 inches; but these data are not of direct relevance to the main purpose of this survey.

For good stability it is important to take precautions.[38] The Mole-Richardson Company quotes long term variations as equivalent to a temperature change of 12°K, measured at $\lambda = 650$ nm, and short term as 2°K; noise ($\gtrsim 6$ c/s) as 3°K. Translated into intensity fluctuations this is approximately a noise level of $\pm$ 1 percent and a drift of $\pm$ 2 1/2 percent (for an unspecified time period).

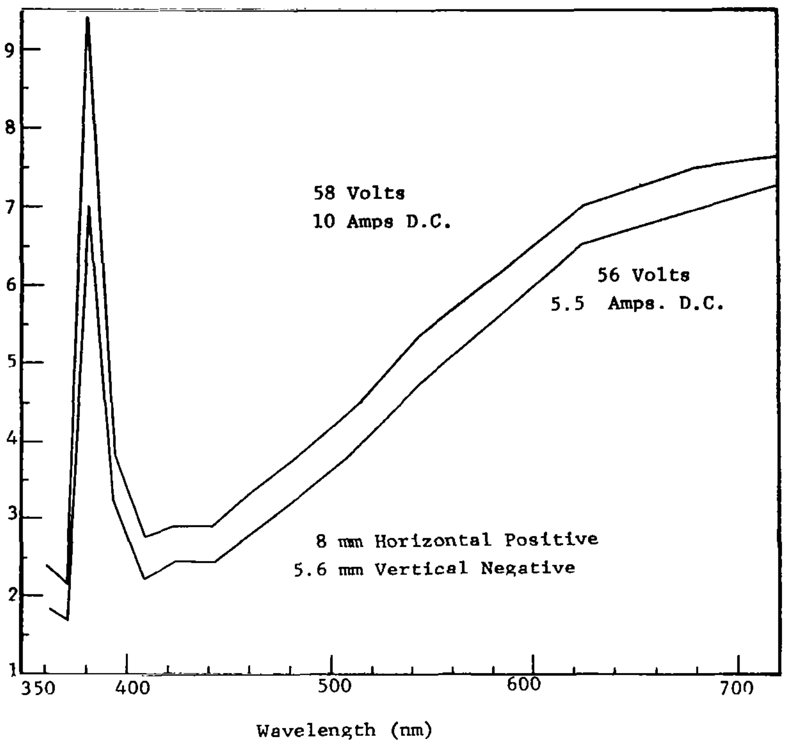

Figure 2.21 Relative Spectral Energy of Bausch and Lomb Carbon Arc (From National Carbon Co. Literature)

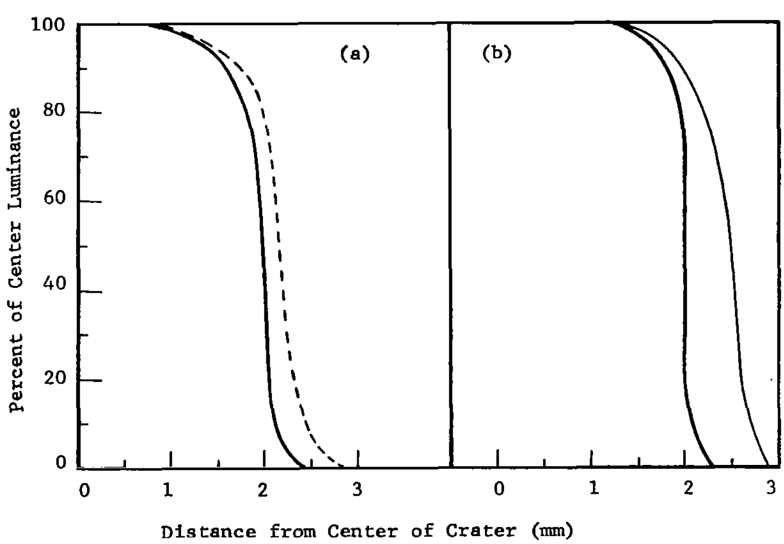

Figure 2.22 Radial Distribution of Luminance Across Crater of Carbon Arc - (Graphite Anode)[38]

(a) 90° Angle - 1/4" Dia.
(b) 120° Angle - 5/16" Dia.

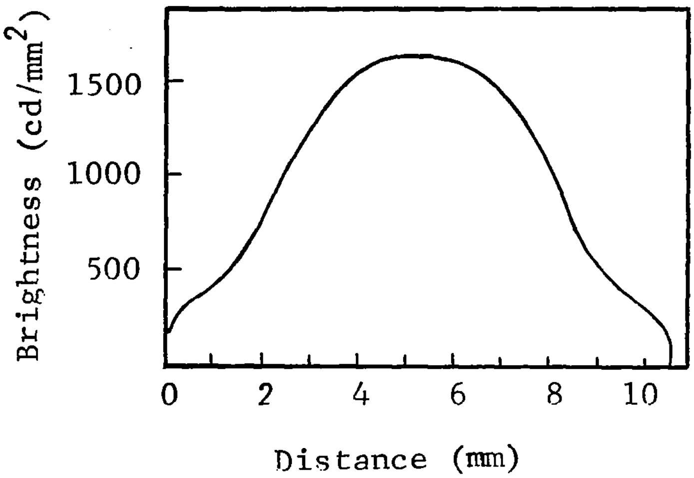

Figure 2.23 Variation of the Brightness Across the Anode Tip of a High Current Carbon Arc[36]

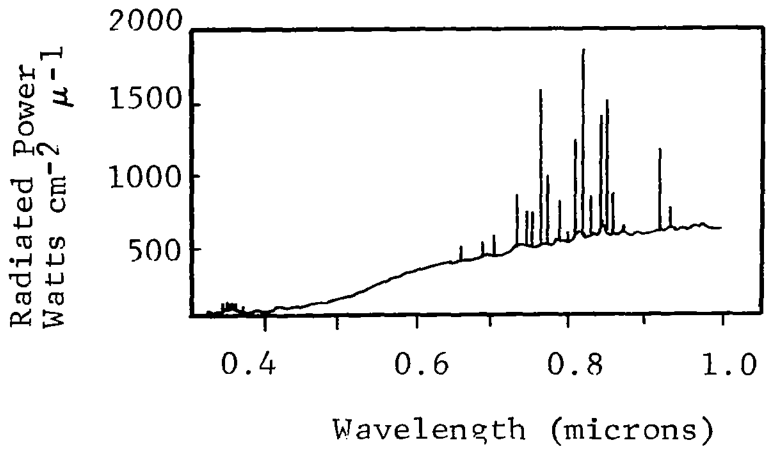

Figure 2.24 Spectral Energy Distribution in the Zirconium Arc (100 Watts)[43]

Bausch and Lomb quote a ripple for their D. C.-42 power supply of less than 0.4 percent. No further information was obtained pertaining to stability but Jaffe[42] has operated a small microscope illuminator arc at 7 amperes, with 6 mm electrodes, and claims properties as good as those obtained by MacPherson with the larger arc.[37]

2.4 ZIRCONIUM ARCS

Concentrated arc lamps using zirconium oxide in the cathode were developed during World War II. A detailed discussion of the construction and performance of these lamps has been given by Buckingham and Diebert.[43] The unique feature of these lamps is the cathode, which is made by packing zirconium oxide into a small cup at the end of a tungsten, molybdenum or tantalum electrode, metals with high melting points. The anode is also a high melting point material and on account of its large surface area, remains relatively cool. The anode is mounted close to the cathode tip and has a hole through which the cathode may be viewed. During operation molten zirconium metal is formed and it is this which is the direct source of visible radiation. The lamps have an argon fill and spectrograms show lines of ArI, ZrI, ArII, ZrII, ZrIII; lines of ArI and ZrII are the strongest.

The spectral distribution obtained from these arcs is shown in Figure 2.24. The continuum radiation is emitted chiefly by the molten cathode surface and peaks at around 1000 nm. The lines are emitted by a cloud of excited gas and vapor near the cathode.

The diameter of the cathode spot depends upon the current: it increases with larger currents and the upper limit is set by the cathode spot completely covering the zirconium oxide surface. Further increase in current makes the spot brighter and shortens lamp life. For small currents the lamp becomes unstable and the spot varies in size. The uniformity of the brightness distribution is shown in Figure 2.25 and the spatial distribution in Figure 2.28.

Variations in the position of the arc stream and irregularities in the cathode surface may produce asymmetry in the brightness distribution and also some instability. The spot position may move slowly during operation by an amount equal to a small percentage of its own diameter. These factors produce variations of about 10% in the emitted light. During the first few hours of operation, the intensity of the emitted radiation and the spot diameter decrease and the brightness increases. After about 100 hours of operation these characteristics are nearly stable with a brightness 1.40 times initial brightness, see Figure 2.26.

The above data were obtained from the paper by Buckingham and Deibert.[43] Since then improvements may have been made but no such data could be obtained from the manufacturers. In fact, the current Sylvania lamps appear to be very similar to those described

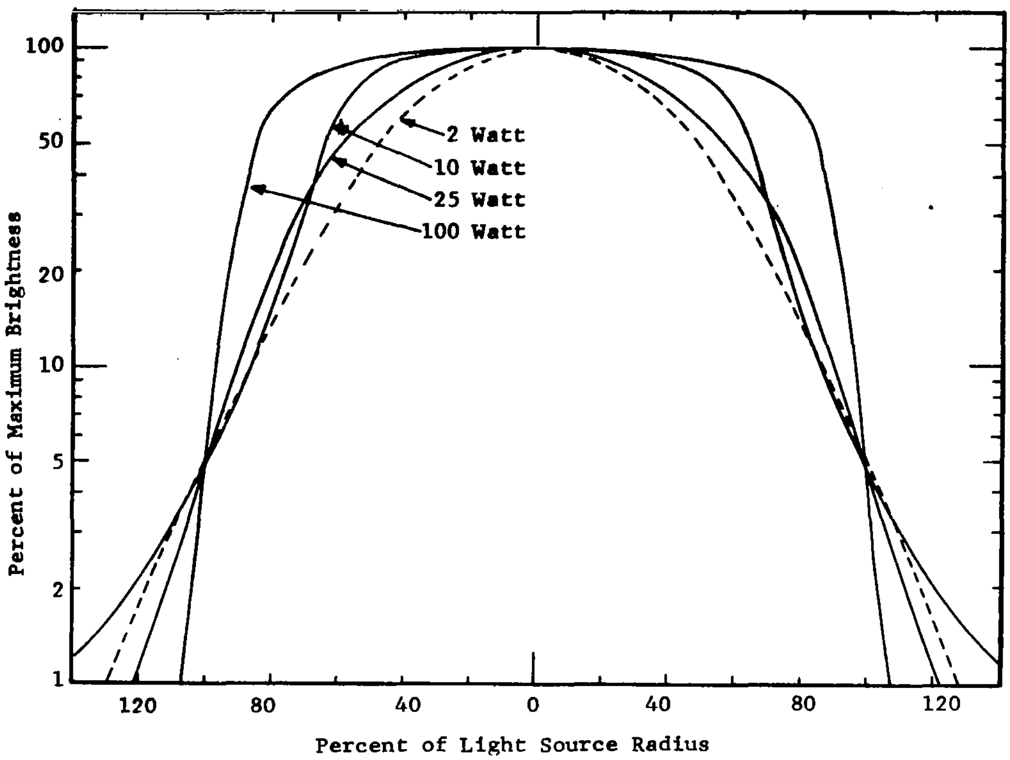

Figure 2.25 Average Cathode Brightness Distribution of Concentrated Arc Lamps[43]

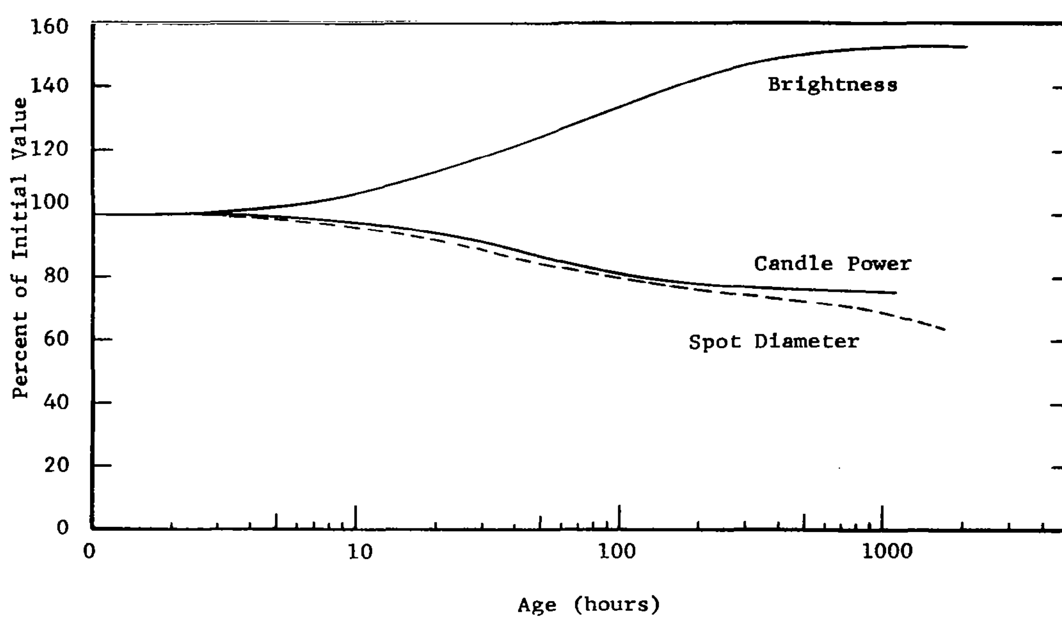

Figure 2.26 Change of Characteristics of Age of 10 Watt Concentrated Arc Lamps[43]

in this paper and Sylvania literature shows the curves given in Figures 2.24 and 2.28. This suggests that the data of Buckingham and Deibert are still accurate.

Table VI shows the arcs marketed by Sylvania Electric Products Corporation. In this table, the designation A, C, K refer to the envelope type and electrode orientation within the envelope; Figure 2.27 shows the output for their lamp type K100Q. For use in the infrared these arcs require modification to take a suitable window. Turrell[44] and Hall and Nester[45] have made such modifications. Turrell modified a Sylvania 300 watt arc and compared the output with a Globar operated at 1175°K. The arc was appreciably stronger as can be seen in Figure 5.3; this figure shows the relative amounts of radiant energy passing the entrance slit of a monochromator, but the zirconium arc did not fill the slit in this experiment due to the small image, so the effect is even greater. The arc operates at a temperature of about 2400°C and so above 10,000 nm scattered light is a more severe problem than for the Globar. Turrell reports that the arc was stable to 2% for periods exceeding an hour; judging from Buckingham's and Deibert's results, this was probably for an aged arc, but still shows an improvement over the earlier results.

TABLE VI SYLVANIA CONCENTRATED ARC LAMPS
(Zirconium Arcs)

	Power (watts)	Mean Light Source Diameter (inch)	Mean Brightness cd mm^{-2}	Average Life (hours)
A2, C2, K2	2	0.005	25	150
C5	5	0.010	37	450
C10, K10	10	0.015	47	450
C25, K25	25	0.030	36	600
C100, K100	100	0.072	39	375
K300	300	0.110	40	250

There is also a K100 Q arc lamp which has a quartz envelope for improved transmission in the ultraviolet.

2.5 Hydrogen Arcs

The hydrogen arc has been widely studied in the laboratory and information is given by Finkelnburg and Maecker[8] or Lochte-Holtgreven,[10] for example. The arc lamps available commercially as light sources are low power devices enclosed in quartz or pyrex envelopes and operating with an independently heated cathode for starting. Commercial arcs are obtainable from the following companies:

i) Bartol Research Foundation, Swarthmore, Pa.
The Nester hydrogen lamp, constructed by Mr. Gerald Fau

ii) Bausch and Lomb Inc., Rochester, N.Y.
Hydrogen

iii) Beckman Instruments Inc., Fullerton, Calif.
Hydrogen and deuterium lamps.

iv) Hilger and Watts, London, U.K. (Engis Equipment Corp., Chicago, Illinois) Deuterium

v) Orion Optics Corp., Stamford, Conn.
Deuterium

vi) Sylvania Electric Products Inc., Ipswich, Mass.

Data on the Nester lamp was not obtained from the manufacturer and that given here is from a report by Amicone, Davey and Franklin.[47] The lamp operates with hydrogen at 0.55 torr pressure and is water cooled. Filament current is approximately 12 amps at 3 volts, it is switched off after the arc strikes. Discharge current is 1 to 1.3 amps at 56 volts D.C. (the arc can be run on A.C. also). In the work reported by Amicone et al, the stability of the lamp was fairly important so that this is probably good.

Bausch and Lomb markets a water cooled hydrogen arc. In spite of requests for information on this lamp none was supplied.

One was viewed briefly, however, and appeared identical to the drawing of a Nester lamp given by Amicone, Davey and Franklin.[47]

Beckman Instruments supplies hydrogen and deuterium filled lamps. The lamps have fused quartz windows, for use down to 185 nm but the hydrogen lamp is also supplied with a specially thin window which transmits useful radiation down to 160 nm. Lamp powers are around 50 watts with lifetime guaranteed to 500 hours. The deuterium lamp is 2.5 times more intense than the hydrogen (spectral effect of this was not given).

Orion Optics Corp., offers two types of deuterium lamps, one with the fused quartz envelope and the other with a suprasil window. These lamps also use a filament for starting (5 amps at 2.5 volts) and are intended to operate at 30 or 60 watts input. The relative spectral intensity is shown in Figure 2.30. The luminous aperture is 1 mm diameter and the rated life 500 hours (to 50 percent of initial output). The manufacturer quotes ripple and noise as 0.1 percent peak to peak.

Sylvania markets three lamps

HAK-50	Hydrogen arc lamp (40 watts D.C.)
DE-50	Deuterium arc lamp (40 watts D.C.)
DE-350	Identical to DE-50 but has UV-transmitting quartz window

All three lamps are of the same construction with a filamentary electron source within a nickel cylinder, the cathode, and an

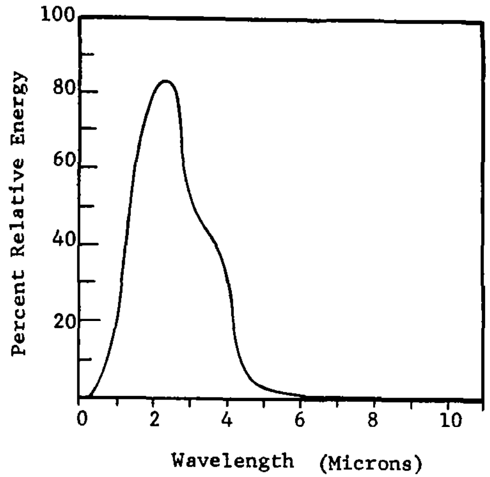

Figure 2.27 Relative Spectral Energy Distribution for Sylvania K100Q Concentrated Arc Lamp

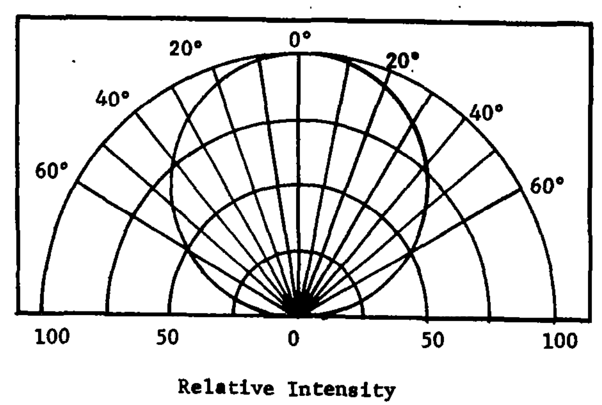

Figure 2.28 Spatial Distribution of Emitted Energy for Concentrated Arc Lamps[43]

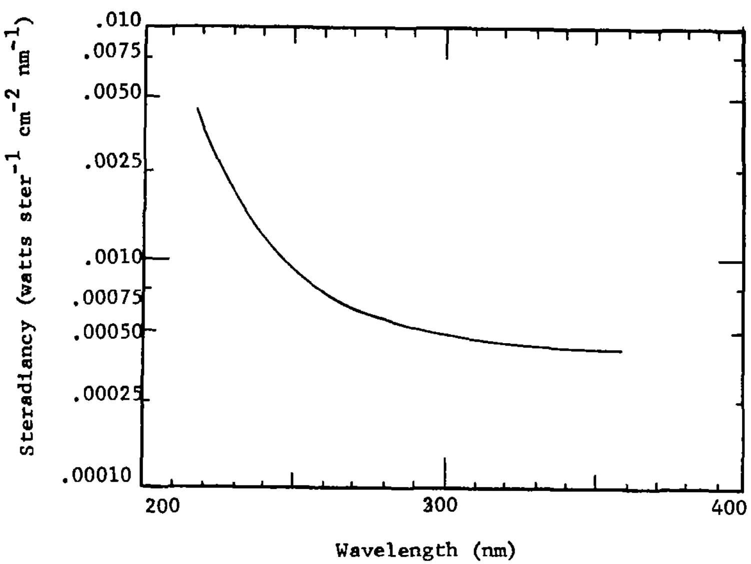

Figure 2.29 Steradiancy of Sylvania Hydrogen Arc Lamp HAK 50 (Sylvania Literature

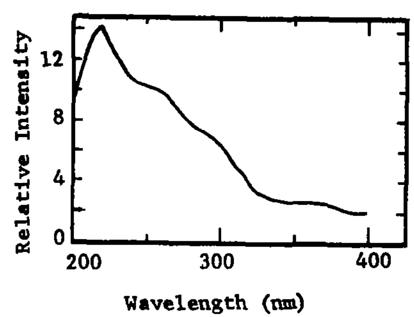

Figure 2.30 Relative Spectral Intensity Orion Optics Deuterium Lamps (Orion Optics Literature)

anode comprising a half-cylinder of nickel and molybdenum. Both electrodes have small holes: that in the anode, through which the light is emitted, is approximately 2 mm in diameter. Emission is into a cone angle of approximately 60° and nominal lamp life is 200 hours, at which time the intensity has fallen by 50 percent. Performance details for the manufacturer's power supply were not obtained. Figure 2.29 shows the spectral steradiancy of the hydrogen arc.

2.6 Argon Arcs

Apparently no such source is supplied commercially (except for the Vortex stabilized source, see Sec 2.7). The reason for including it here is that it has been developed to a very stable form in several laboratories for use as a spectroscopic source. In addition, this arc appears promising as a continuum light source for the ultraviolet, where the intensity of incandescent emitters falls very rapidly as the wavelength decreases; relatively weak discharge sources are normally used in this wavelength region.

Many laboratory studies have been made on argon arcs, and their properties have been described by Goldman,[48] Olsen,[46-48] and others. Olsen has built a highly stable arc for spectroscopic studies. Shumaker[50] has described a copper disc arc for studying various gases, using an inert gas to blanket the electrodes for their protection.

Shumaker's arc is confined to a channel 3/16" diameter, defined by water cooled copper rings, and the arc length could be as great as 10 cm. The current fluctuations were kept low by using batteries. Some drift was observed, however the NI line at 493.5 nm was observed to have fluctuations of ≤ 3 percent (peak-to-peak).

The arc described by Olsen is worth considering in this report. This is a free-burning arc between a 1/8 inch tungsten rod cathode (1 percent thoriated) and a copper plate for the anode, both were water cooled. The separation of the electrodes was 5 mm and the arc operated at 400 amperes and 1.1 atmospheres of argon. By using the thoriated tungsten cathode ground to a 60° conical tip and passing the argon gas over a heated titanium getter, before admitting it to the arc, it was possible to produce a very stable arc plasma. During 100 hours of operation there was less than 10^{-2} gm total weight loss from the cathode and no measurable change on the anode surface. The measured arc voltage varied by less than one percent over day long periods of operation and it was possible to extinguish the arc, replace the cathode and re-strike with the measured voltage and radiation intensity within $\pm$ 3 percent of the previous value. Measured absolute spectral line intensity at the beginning and end of a two day period of continuous operation was also reproduced within $\pm$ 3 percent of their maxima. Olsen ascribed the good stability primarily to the high purity of the gas comprising the plasma and to the favorable volt-ampere characteristics of the arc and power supply. In conjunction with the high emission intensities obtained these are attractive features for a light source. There is a drawback, the arc has large temperature gradients, consequently the uniformity of emission across an effective emitting area is poor. Dickerman and Deuel[51] have used a similar arc. They do not give details in their paper but it is essentially similar to Olsen's.[52]

Olsen's data[46] on his arc include emission intensities for several lines and also for the continuum at $\lambda = 553.5$ nm. He also gives temperature contours for the arc. The spectrum of the arc is characterized by the lines of ArI and ArII superimposed on a background continuum. For a general light source the lines are less important than the continuum since they must correspond to the wavelength of a characteristic feature of the system being studied--a possible exception being scattering phenomena. Consequently, it is the continuum which is of most interest, especially regarding possible use in the ultraviolet.

The temperature distribution found by Olsen is shown in Figure 2.31, and the variation of line and continuum intensities with temperature in Figure 2.32. The intensity emitted by the arc is obtained by integration of such intensity profiles through the arc, making allowances for self-absorption as necessary. For the continuum at 553.5 nm the self-absorption was considered

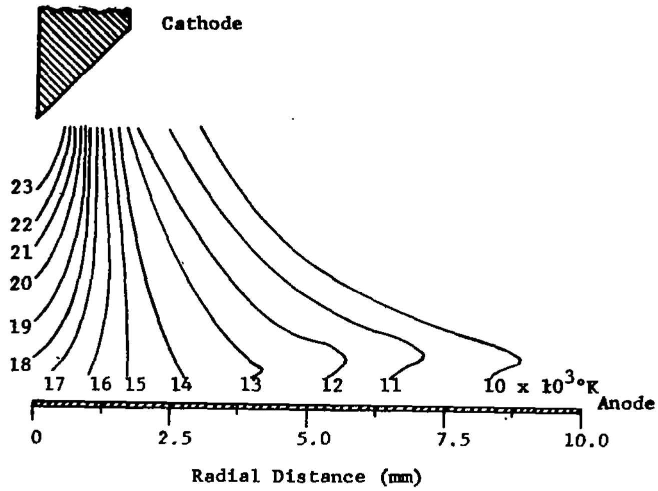

Figure 2.31 Temperature Distribution in the Argon Arc (Olsen[46])

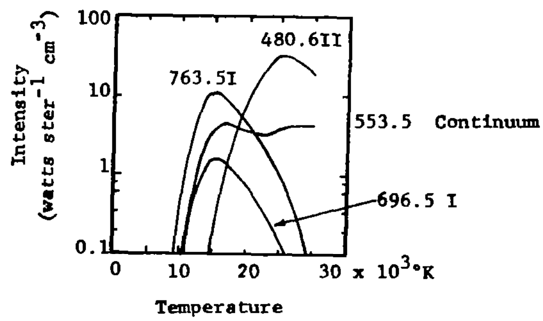

Figure 2.32 Line and Continuum Intensities as Functions of Temperature for the Argon Arc (Olsen[46])

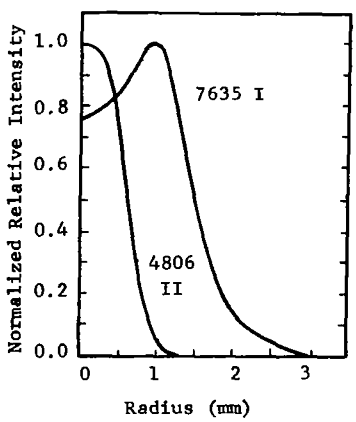

Figure 2.33 Integrated Radial Intensity Distributions for Atomic and Ionic Lines[46]

negligible by Olsen, but not for the line emission.

Detailed calculations on the emission characteristics of the continuum could be made but this is a lengthy procedure; for the purposes of this survey it is interesting to view the possibilities of such an arc as a light source for the ultra-violet, by making approximate calculations based on several simplifying assumptions. This has been done and the details appear in Appendix A. Figure 5.2 shows the results.

Olsen gives absolute emission data and line profiles for the 696.5 and 763.5 nm ArI lines and also the intensity of the 480.6 nm ArII line. In addition, he tabulates transition probabilities measured by himself and other workers. With these data it is possible to compute the emission intensity of these lines and also to obtain approximate values for the steradiancies (watts cm^{-2} $sterad^{-1}$ nm^{-1}). Rough calculations show that the line and continuum intensities are of similar order of magnitude. This makes the argon arc a very useful steady state source of high intensity lines in the range 200-1000 nm (ArI and ArII). Olsen gives data on lines in the range 394.9 nm to 965.8 nm. In the region 150-200 nm there are some 26 lines but nearly all are ArIII,[53] which would probably be much weaker than the other lines given above; Table VII gives the relative populations of argon ions.

TABLE VII RELATIVE POPULATIONS OF ARGON IONS.[46]

(P = 1.1 Atm)

T	ArIV/ArI	ArIII/ArI	ArII/ArI
10,000°K		1.32×10^{-10}	2.04×10^{-2}
15,000	3.72×10^{-14}	6.48×10^{-5}	1.37
20,000	9.60×10^{-7}	0.389	25.8
25,000	2.03×10^{-2}	4.44	7.99

The integrated intensities (i.e. as measured directly) for an atomic and ionic line are shown in Figure 2.33. From these it is seen the arc is quite non-uniform. The continuum profile, at $\lambda = 553.5$ nm, is similar to the atomic line in this figure but increases again at the center. Data for other regions of the arc were not available but Figure 2.33 shows that, for the atomic lines, uniformity to within $\pm$ 5 percent is obtained for a circle of diameter 1.4 mm; strictly only the dimension across the arc can be considered, but the variation in the direction of the arc axis is probably similar. For the continuum the uniformity is probably a little worse.

2.7 Vortex Stabilized Arcs

Such arcs rely on gas or liquid (water) vortex motion to stabilize the position of the arc.[8, 9, 10] Recently an arc stabilized by high pressure gas has become available commercially from Giannini Scientific Corporation, Santa Ana, California. This arc (trade name VSRS) is available for operation at 5, 10, 20 or 25 Kwatts, and up to 150 Kwatts on special order. Figure 2.34 shows the arrangement of the arc which is contained within two fused silica envelopes. The high pressure gas flows between these envelopes, providing thermal insulation, and is introduced around the cathode, forming a vortex which contains the arc. The exhaust gases are extracted through the hollow anode.

The arc can be obtained mounted in an illuminator. This is a double-walled stainless steel chamber (12" diameter for the one used with the 20 Kwatt arc) with a spherical mirror behind the arc and a lens system for focusing the emitted light.

The maker's curves for the spectral distribution of output intensity are shown in Figure 2.35, and the angular distribution in Figure 2.36. The fused silica envelopes cut off radiation below 200 nm; Giannini has also built a unit with a lithium fluoride window and can supply this for special purposes.

The arc size is about 3 mm diameter x 10 mm long for the 25 Kwatt source, and the radiance is nearly uniform along its length.

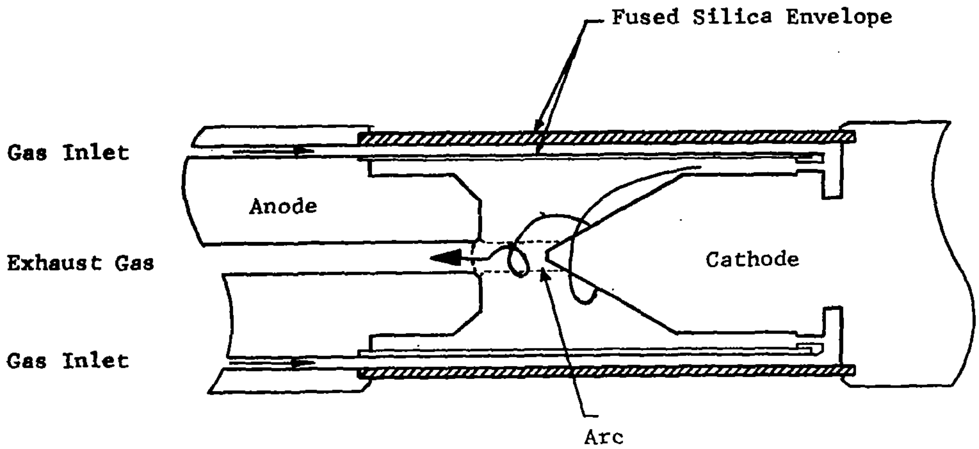

Figure 2.34 Giannini Vortex Stabilized Radiation Source

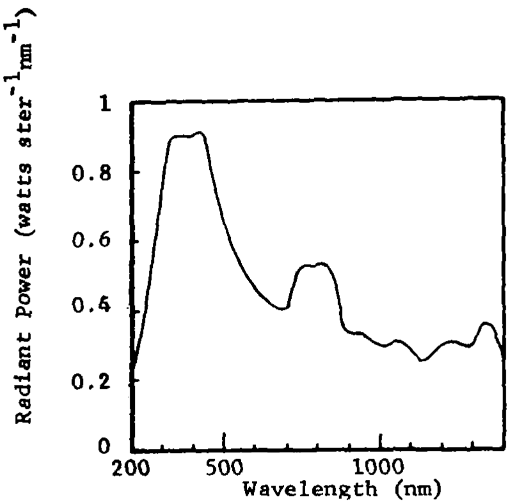

Figure 2.35 Spectral Intensity Distribution for 17 Kwatt VSRS Viewed at 90° to the Axis. Arc Size 10 mm x 1.8 mm (Giannini Literature)

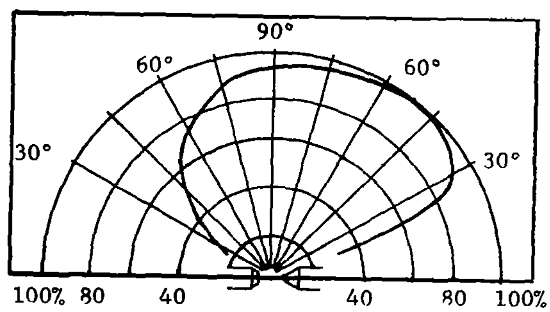

Figure 2.36 Angular Distribution of Radiation Intensity for VSRS (Giannini Literature)

Ripple in the output radiation is given at <1 percent (peak to peak) for the 20 Kwatt system (Model 11806), the makers state that power supplies with less than 0.1 percent ripple are not available. Uniformity of output to within 1 percent for five minutes is considered practical by the makers, provided that the line voltage is reasonably steady, or corrected for variations. Random fluctuations are less than 1 percent.

The lifetime of a 25 Kwatt arc is in excess of 100 hours, when operated continuously. When excess electrode erosion and tube darkening occur, these can be replaced.

The properties of the VSRS have been investigated by Neuder and McIntosh.[54] Figure 2.37 from their report shows the variations of the radiance over the emitting region of the arc, radiance contours are given in Figure 2.38. The total irradiance was measured by a thermopile and the variations with input power and gas (argon) pressure are shown in Figure 2.39.

Neuder and McIntosh made measurements (described by them as preliminary) on the spectral distribution, presumably of irradiance - Figures 2.40, 2.41, and 2.42 were taken from their paper. The discrepancies between the manufacturer's curve, Figure 2.35 and Figure 2.42 are probably primarily due to resolution differences.

Neuder and McIntosh found the stability over several hours to be around $\pm$ 2 percent. Electrode damage after 100 hours of operation was moderate.

2.8 Special Arcs for the Vacuum Ultraviolet

In the present survey this is the region 150-200 nm, but such arcs are intended for use to lower wavelengths.

No such arcs were found to be available commercially, with the exceptions mentioned earlier where modifications can be made to other types (e.g. suprasil envelopes for compact arcs). Boldt[55,56] has described a cascade arc which is equipped with interlocks and buffer gases to maintain transparency to the radiation.

The magnetically confined vacuum arc has been described by Burns et al,[57] for example. The arc is stabilized by a solenoid-generated magnetic field, may be very long (apparently the length is limited by construction and operation problems only), and may be operated at very low pressures. Such an arc has great potential for the excitation of radiation in the far ultraviolet.

Another arc which may be used is the duoplasmatron,[58] but this appears to be more suitable for exciting line radiation at short wavelengths.

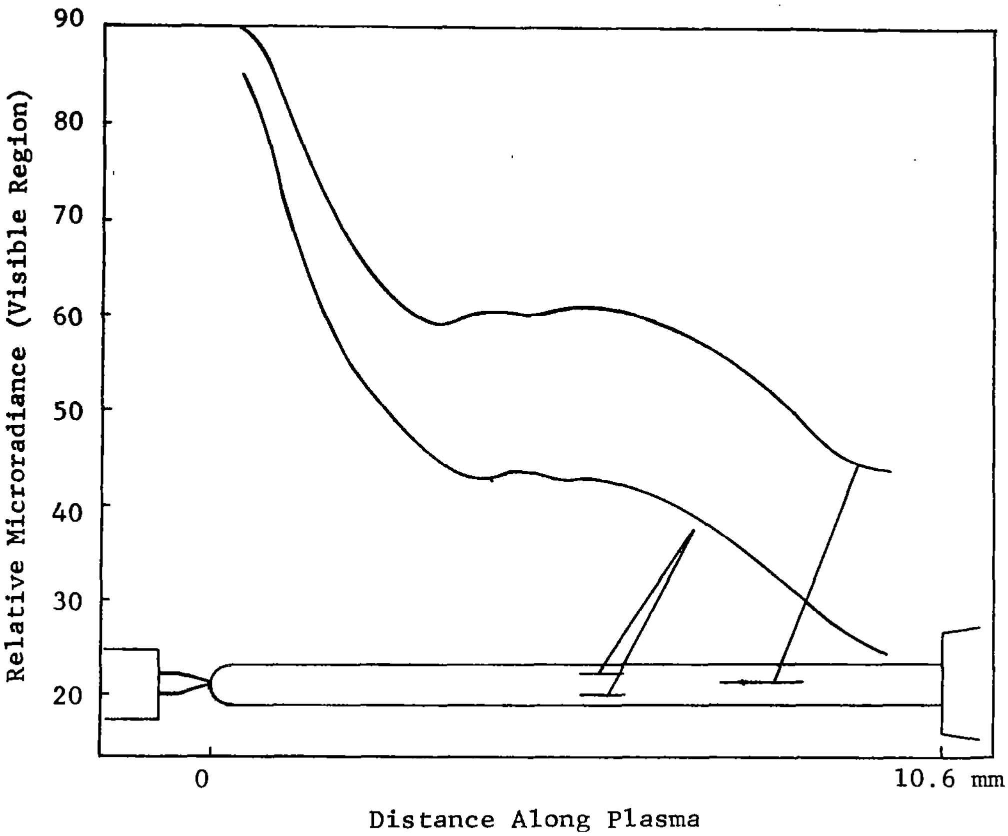

Figure 2.37 Relative Microradiance of 4 Kwatt VSRS[54]

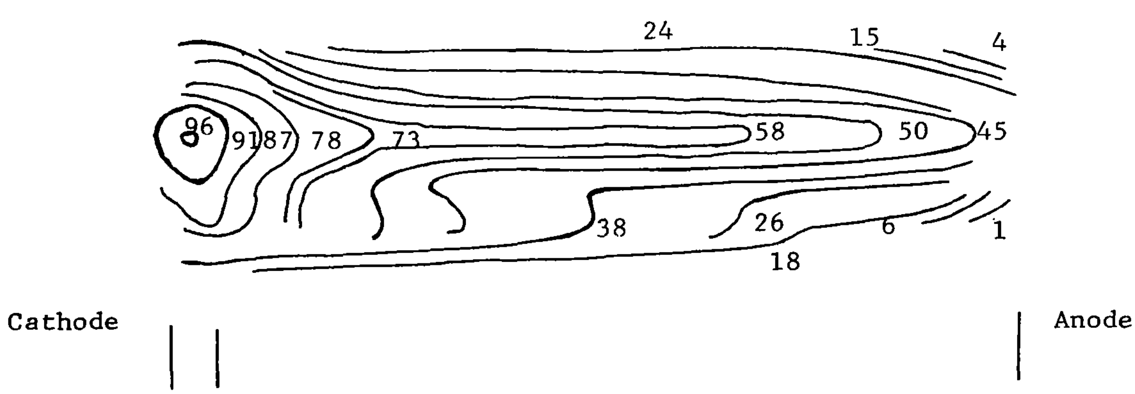

Figure 2.38 Isoradiance Contours for the VSRS. Argon 4 Kwatt, 8.4 Atmospheres. (Arbitrary Units)[54]

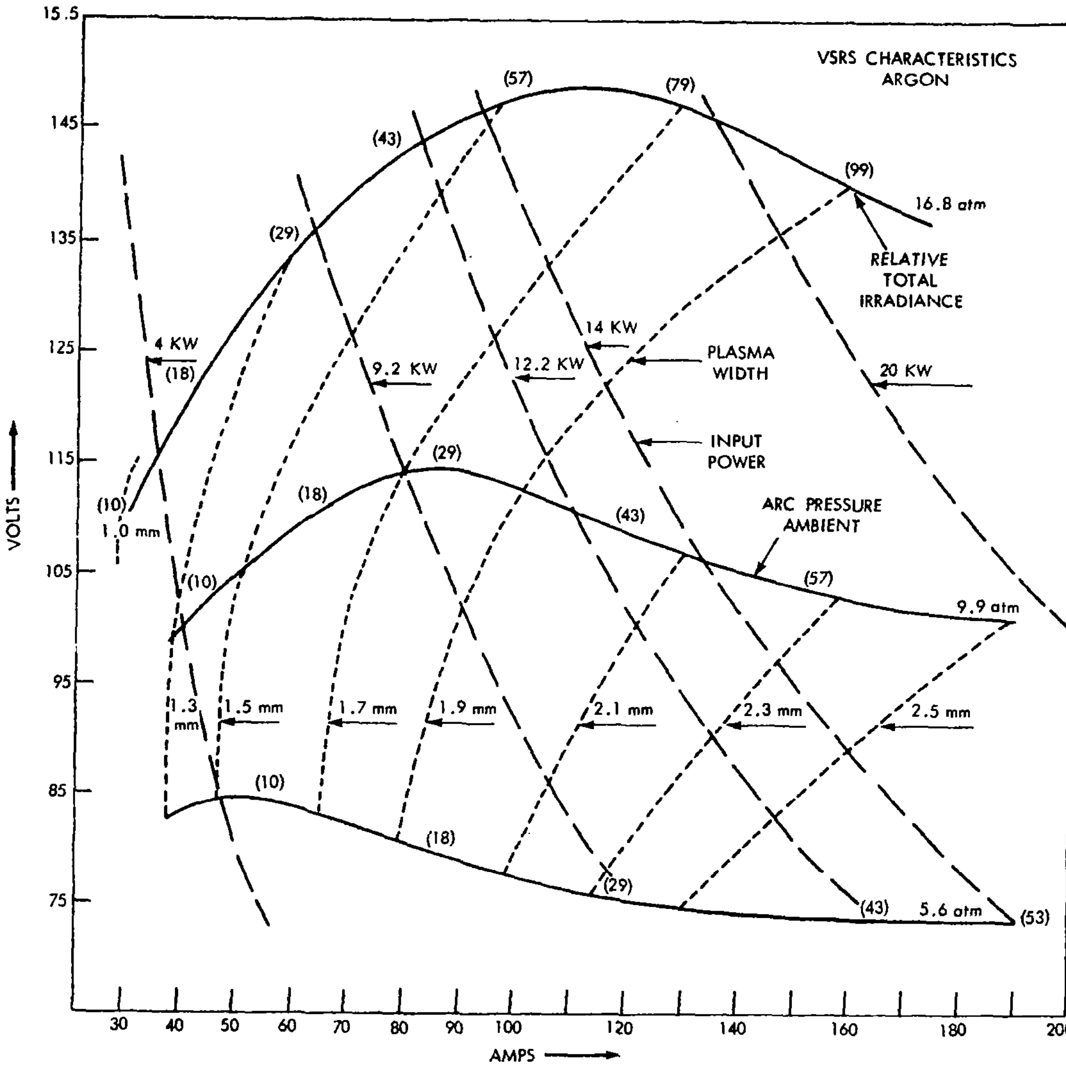

Figure 2.39 VSRS Operational Parameters[54]

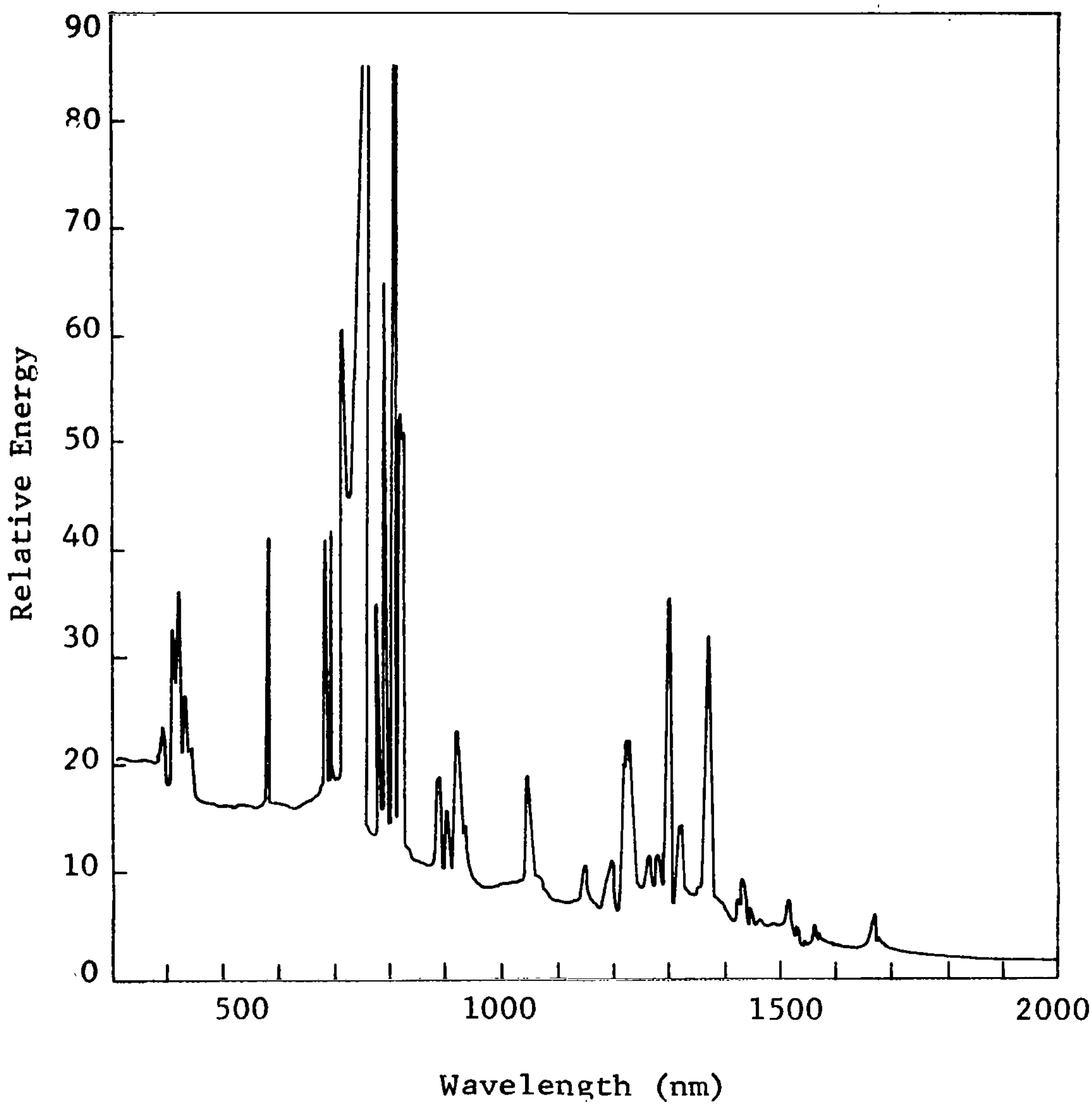

Figure 2.40 Spectral Distribution of 4.5 Kwatt VSRS with 5.5 atm of Argon.[54]

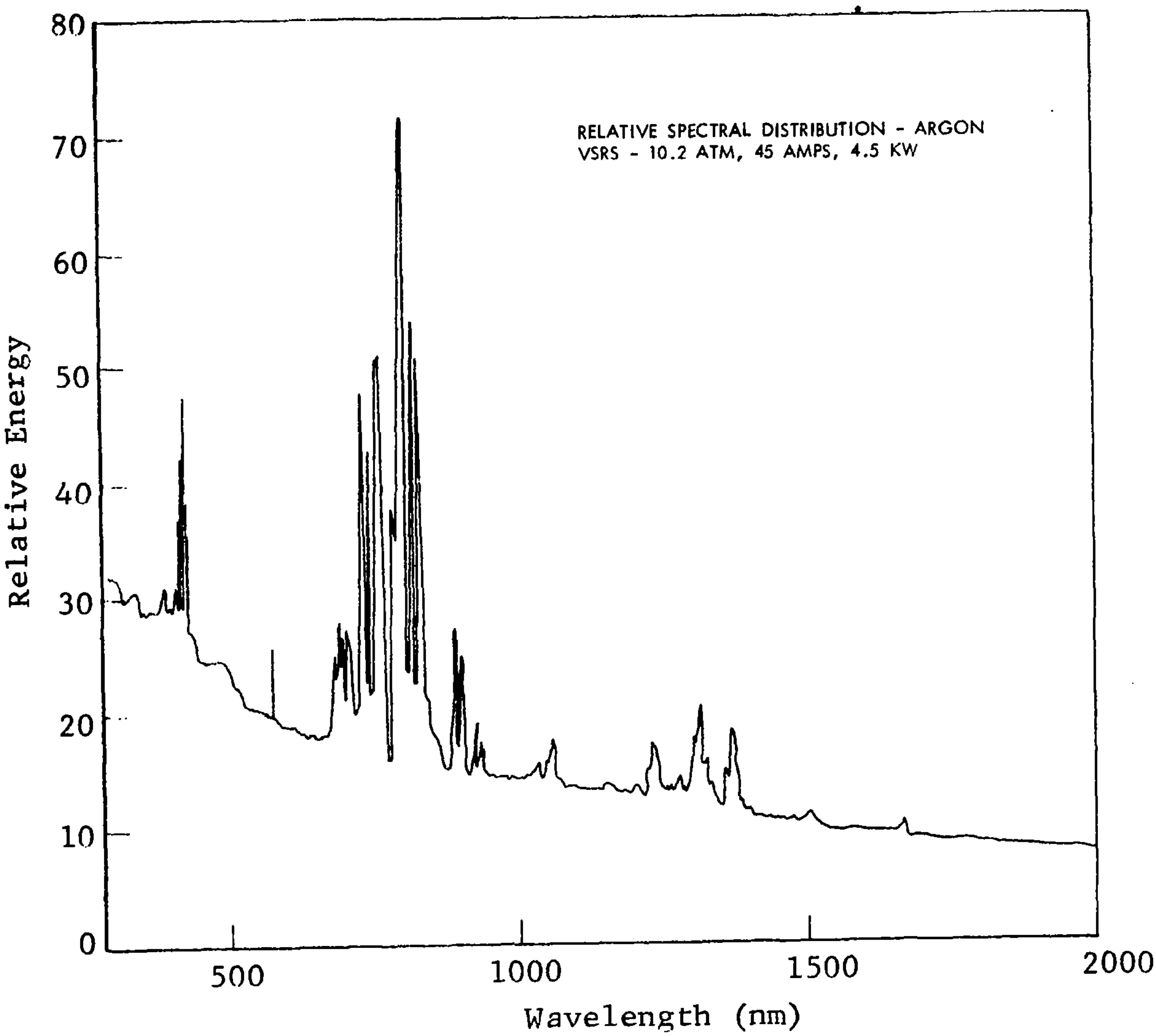

Figure 2.41 Spectral Distribution of 4.5 Kwatt with 10.2 atm of Argon[54]

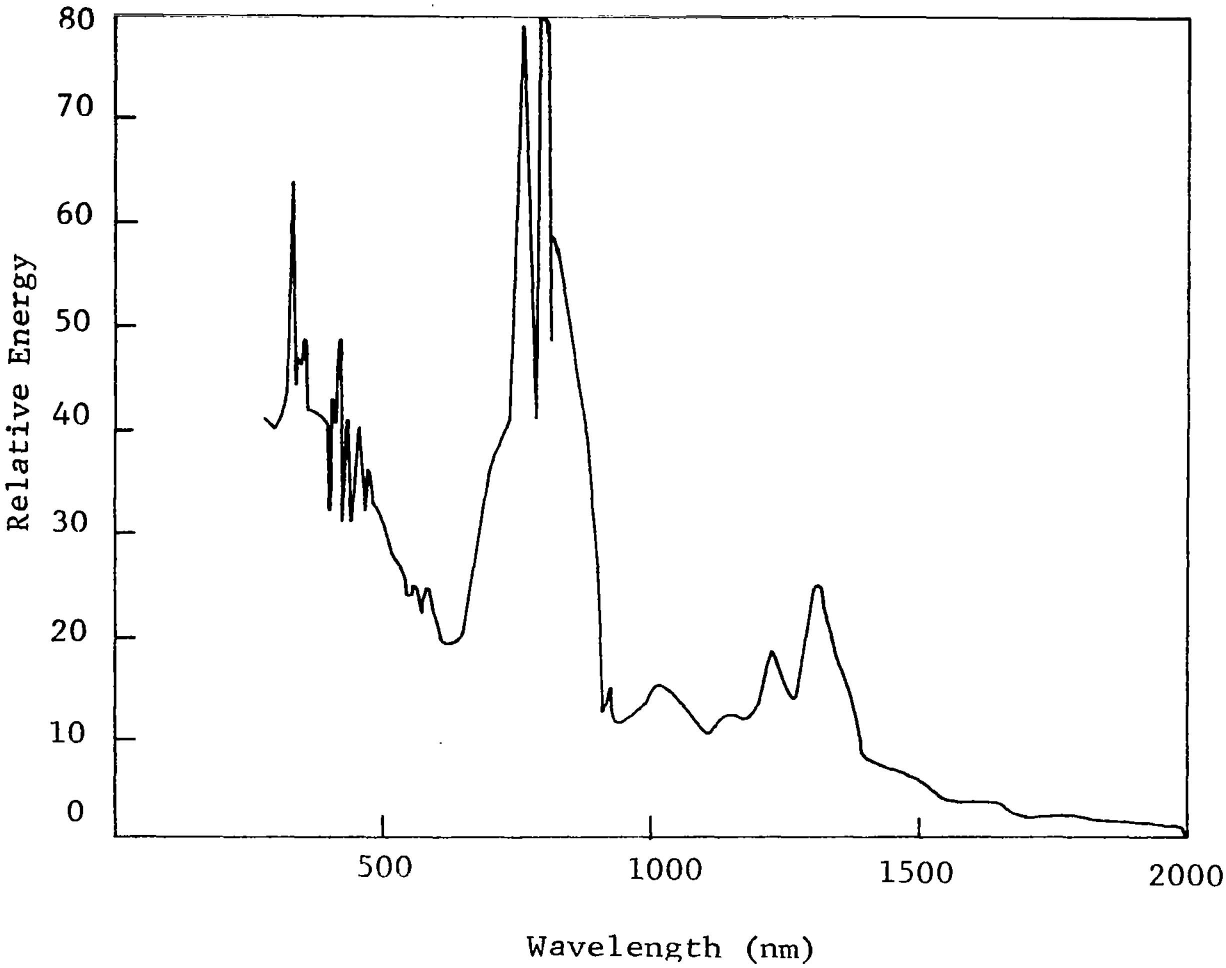

Figure 2.42 Spectral Distribution of 18.2 Kwatt VSRS with 16.8 atm of Argon[54]

3. INCANDESCENT SOURCES

3.1 General

Certain types of arcs fall into this category, but these have already been discussed. The sources considered in this section are:

Blackbody

Tungsten filament and ribbon lamps

Globar

Nernst glower

The carbon filament lamp, which is a standard of irradiance and available from the Eppley Laboratory Inc., for example, is not of direct relevance here and will not be considered.

In various forms the tungsten lamp is very widely used commercially and a large number of types are available. Most of these are of little interest as laboratory sources and have been developed for special lighting purposes. The other three types of sources are of particular interest as infrared sources and are widely used.

3.2 Black-Body Sources

3.2-1 General

The manufacturers from whom data were obtained are the following:

1. Astro Industries, Inc.
   Santa Barbara, California

2. Barnes Engineering Co.
   Stamford, Connecticut

3. Electro-Optical Industries Inc.
   Santa Barbara, California

4. Infrared Industries Inc.
   Santa Barbara, California

5. Rocketdyne
   Canoga Park, California

These sources consist essentially of a heated cavity, so designed that the emissivity is independent of age and the nature of the walls and is nearly unity. For use as a blackbody source it is important that the temperature be known and that the source be highly stable. The sources are commonly constructed of graphite and over 2500°K the vapor pressure of carbon becomes appreciable, hence high temperature furnace sources of this type generally have a short life. The life can be lengthened somewhat by operation with a high pressure inert gas within the furnace and this is done in some cases.

Table VIII lists the salient features of sources for which data were obtained.

TABLE VIII

BLACK-BODY SOURCES

Manufacturers	Model	Temperature Range	Cavity Length (ins)	Aperture* Dia.(ins)	Emissivity	
Astro-Industries	2570	300-3000°C	Cyl: 4.0	0.5	0.99	
			Cone (30°): 3.36	0.75	0.99	Inert gas 2700°C
Barnes Engineering	11-101T	0-230°C	Cone (14°)	0.625	0.99 ± 0.01	Down to 20°C Above Ambient
	11-110T	200-600°C	Cone (28°)	0.5	0.99 +	
	11-119T	200-600°C	Cone (14°)	0.0086	0.99 +	
	11-120T	200-600°C	Cone (14°)	0.015	0.99 +	
	11-121T	200-600°C	Cone (14°)	0.040	0.99 +	
	11-200T	200-1000°C	Cone (28°)	0.5	0.99 ± 0.01	
	11-201T	200-1000°C	Cone (28°)	1.0	0.99 ± 0.01	
Electro-Optical Industries	111	50-600°C	Recessed Cone	0.040	0.99 ± 0.01	
	121	50-600°C	Recessed Cone	0.080	0.99 ± 0.01	
	131	50-600°C	Recessed Cone	0.25	0.99 ± 0.01	
	141	50-600°C	Recessed Cone	0.50	0.99 ± 0.01	
	181	50-600°C	Square	4	0.90 - 0.98	
	191,192, 193,194	50-600°C	Recessed Cone	0.080	0.99 ± 0.01	
	113	50-1000°C	Recessed Cone	0.040	0.99 ± 0.1	
	123	50-1000°C	Recessed Cone	0.080	0.99 ± 0.1	
	133	50-1000°C	Recessed Cone	0.25	0.99 ± 0.1	
	143	50-1000°C	Recessed Cone	0.50	0.99 ± 0.1	
	153	50-1000°C	Recessed Cone	1.0	0.99 ± 0.1	
	173	50-1000°C	Recessed Cone	3.0	0.99 ± 0.1	
	183	50-1000°C	Square	4	0.90 - 0.98	
	115	1000-2000°K	Recessed Cone	0.040	0.99 ± 0.1	
	125	1000-2000°K	Recessed Cone	0.080	0.99 ± 0.1	
	135	1000-2000°K	Recessed Cone	0.25	0.99 ± 0.1	
	145	1000-2000°K	Recessed Cone	0.50	0.99 ± 0.1	
	155	1000-2000°K	Recessed Cone	1.0	0.99 ± 0.1	
	146	1000-3000°C	Recessed Cone	0.50	0.99 ± 0.1	
Infrared Industries	403	325-1000°K		0.5	0.99 ± 0.01	
	404	50-1000°C		0.5	0.99 ± 0.01	
	405	325-1000°K		1.0	0.99 ± 0.01	
	406	50-1000°C	Recessed Cone (20°)	1.0	0.99 ± 0.01	
	407A	200-600°C		0.08	0.99 ± 0.01	
	408	200-600°C		0.250	0.99 ± 0.01	
	417	50-1000°C		3.0	0.99 ± 0.01	
	420	200-1200°C		0.5	0.99 ± 0.01	
	427	200-600°C	3.5	0.08	0.99 ± 0.01	
Rocketdyne		up to 3100°K	Cylinder	0.25	0.99	
		up to 2200°K		2.00	0.975	
		up to 2500°K	Slit along tube length	0.25x0.03	0.975	Slit source

*Maximum is given. Some models have variable apertures.

The Astro Industries Model 2570 C Laboratory Furnace may be used as a radiation source for temperatures up to 3000°C. Up to 2700°C the furnace may be operated with a vacuum, but from thereon up an inert or reducing atmosphere (up to 45 psi) is used and the radiation must pass through a quartz window. The source has been described by Witucki[59] and by Knapp;[60] both these documents were supplied by the manufacturer. The cavity described by Witucki is a graphite cylinder 4.0 inches long and 0.5 inches in diameter, which is viewed through a 0.75 inch diameter tube of similar length at the end of which a window may be placed, this is necessary at temperatures above 2700°C. The calculated emissivity of this cavity was 0.994 and 0.99 by different methods; at such high values of emissivity the precise value would be determined by temperature gradients over the surfaces, rather than the cavity geometry. For this cavity the maximum deviation from the control temperature was less than 0.4 percent up to 1395°C (2543°F).

Knapp[60] gives data on a conical cavity of 15° half-angle and cone length of 3.36 inches, stopped down to a 0.750 inches aperture. Measurements were made at temperatures up to 3000°C. Calculated emissivity was 0.99.

The Barnes Engineering literature describes several models of blackbody source. These employ closed-loop temperature control for high stability. Models of interest here are listed in

Table VIII. These have a recessed conical cavity as standard but Models 141-145 can be supplied with cylindrical or spherical cavities, if required. These sources are not supplied with thermocouples except in the cases of Models 133, 141, 142, 143, 153 and 173. In addition to the sources listed in Table VIII, the manufacturer states that additional models have been developed including miniature sources with cavity diameters of 0.005, 0.010, and 0.020 inches, for operation up to 1000°C. They have also developed cold environment sources for use in ambients at liquid nitrogen temperatures, with temperatures variable from 150°K to 600°K.

Rocketdyne make sources to order and descriptions of three types were supplied. Argon purge is used. The 1/4-inch diameter source is described in a report by Schumacher,[61] and the slit source by Simmons, DeBell and Anderson.[62] Additional information was supplied by Schumacher.[63]

The high emissivities of the cavity-type sources is due to the cavity design, since the emissivity of graphite is about 0.85.[62] The emissivity of graphite is a slowly varying function of temperature and so, since its effect is only secondary, these cavities emit essentially as grey bodies with emissivity around 0.99.[63]

TABLE IX FIELDS OF VIEW OF BLACKBODY SOURCES

	Model	Cone Angle
Astro Industries	2570	10°*
Barnes Engineering		
Electro-Optical Industries	125,146	5°
	111,113,115,121,123	5°
	135,145,191,192,193	10°
	194	10°
	133,141,142,143,144	10°
	155,173	15°
	153	30°
	131	45°
	181,183	90
Infrared Industries	403,404,420	14°
	405,406	30°
	408	Wide
Rocketdyne	1/4" aperture	6.5°
	2" aperture	27.75°
	Slit aperture	65°

* Calculated from manufacturer's drawing of source.

3.2-2 Uniformity

Schumacher states that no temperature variation was observed over the 1/4 inch diameter and slit Rocketdyne sources; for the 2-inch aperture variations of $\pm$ 16°K were detected at 2200°K. In terms of radiative output this amounts to $\pm$ 4.5 percent across the source.

The angular variation is given as cosine by Electro-Optical Industries, which is what one would expect for a perfect blackbody; some deviations might be found for large apertures but these were not mentioned. The fields of view for the various sources are given in Table IX.

3.2-3 Stability

All sources listed in Tables VIII and IX were powered by A.C. The heating was indirect in all cases so a ripple in the output is not to be expected. Astro Industries and Electro-Optical Industries report that they had not detected any such ripple. Simmons, DeBell and Anderson[62] quote a time constant of 10 seconds and Schumacher estimates that ripple in the output of the 1/4-inch diameter source would be less than $\pm$ 0.01 percent.[63]

Temperature stabilities quoted are as follows:

1. Astro Industries: $\pm$ 0.1% 300-3000°K

2. Barnes Engineering: ± 1°C Model 11-101T

± 0.1°C Model 11-110T

± 1°C Models 11-200T

11-201T

± 0.1°C Models 11-119T, 11-120T

11-121T

Shift in line voltage and ambient conditions could cause changes up to ± 3°C.

3. Electro-Optical Industries: within 0.1°C

4. Rocketdyne: Temperatures were within accuracy of measuring pyrometer (± 5°C) over hundreds of hours.

3.2-4 Lifetime

This is measured in hundreds of hours and end of life usually means easy replacement of the cavity. Astro Industries report no measurable coating of the quartz window during high temperature operation, which is probably due to their gas purge blowing across the window.

Specifically, Electro-Optical Industries quotes 200-500 hours of life. Schumacher[63] states that the 1/4-inch source was operated continuously at 2000°C for over 700 hours with no detectable change in characteristics. Similarly the 2-inch aperture source was operated for several hundred hours up to its maximum temperature, and slit type sources have been run for 200 hours at 2000°C. At the highest temperatures the lifetime fell appreciably but little data were available -- tests indicated at least 5 hours stable operation at 3000°K for the 1/4-inch aperture.

3.3 Tungsten Filament Lamps

Tungsten filament lamps are made in many different forms for use by industry and other consumers. The coiled filament is generally out of the range of sources reviewed in this report, on account of the non-uniformities introduced by the coils. It is quite probable that this non-uniformity may be small in the case of the "coiled coil" type, possibly with reflector, but the matter was not investigated. A coiled filament lamp has been established as a spectral standard of irradiance and this is discussed. A good discussion of the types of lamps available has been given by Carlson and Clark.[6]

3.3-1 Ribbon filament lamps

These are well known and are widely used as sub-standards of spectral radiance. The lamp can be purchased with a calibration curve showing the temperature as a function of current, calibrated by the National Bureau of Standards. As such, these lamps are known for highly stable operation and predictable spectral radiancy. The emissivity of tungsten is shown in Figure 3.1 obtained from the graphs published by De Vos;[64] more recent measurements have

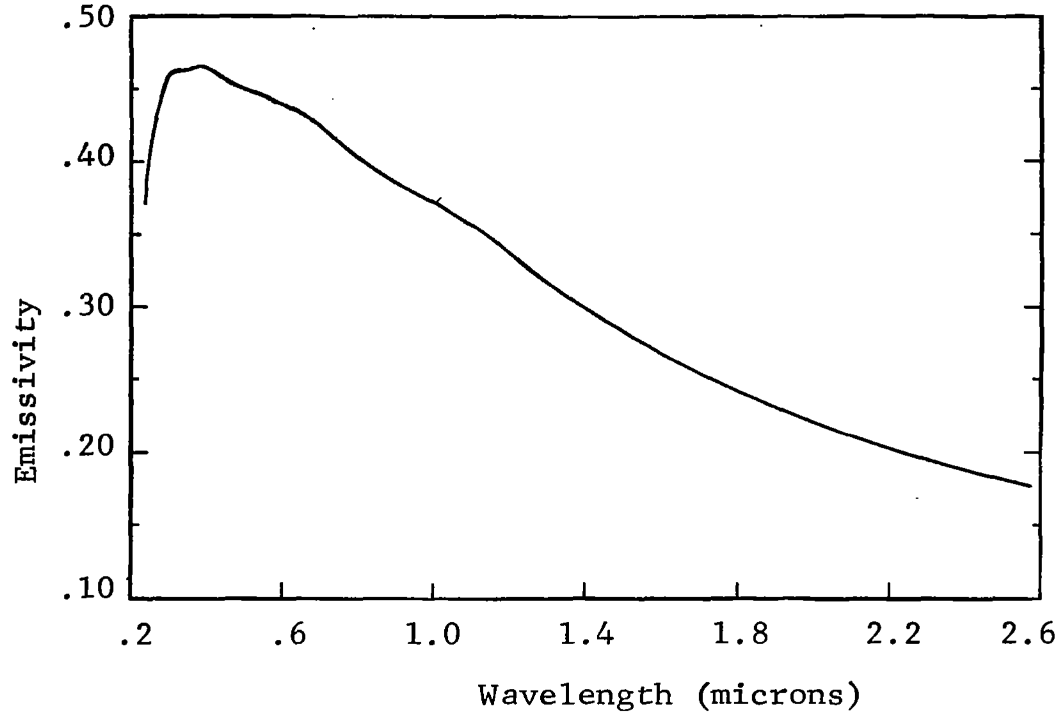

Figure 3.1 Emissivity of Tungsten at 2600°K[64]

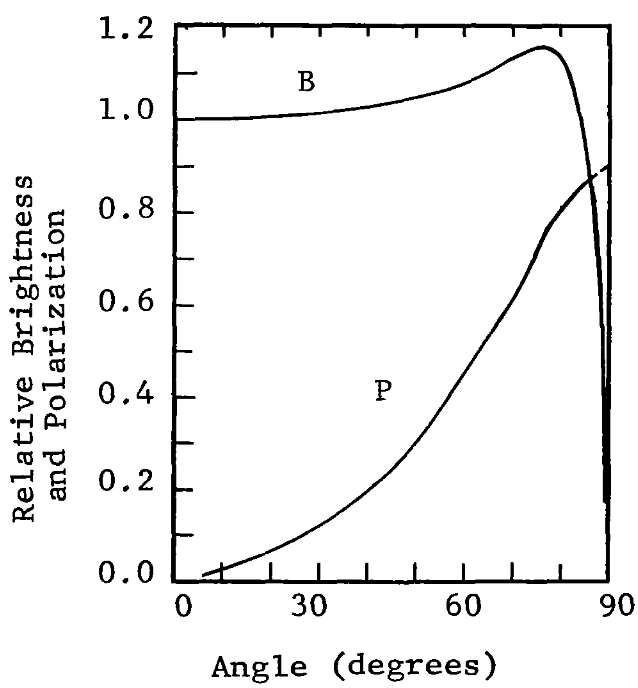

Figure 3.2 Brightness and Polarization of Tungsten[67]

been made e.g. Larrabee for wavelengths between 310 to 800 nm.[65] If the true temperature of the ribbon is known, then the radiance can be computed from blackbody relations and the emissivity curve. Standard tungsten lamps are supplied for the spectral range 250 to 2,600 nm in two ranges, 250 to 750 nm and 500 to 2,600 nm.[66]

The ribbon in such lamps is always at a non-uniform temperature, thus only the central area is calibrated. Ribbon widths are typically about 2 mm and different lengths can be supplied. Output variation as a function of angle follows the cosine law approximately but may depart from this at large angles.[64] Maximum color temperatures for standard lamps are about 3,000°K and these should be maintained only briefly.[66] Non-standard filament lamps may be operated at higher temperatures, of course, but with loss in life. For example, a 18-ampere General Electric lamp has a life of 60 hours at a color temperature of 3200°K (corresponding to a current of about 20 amperes) but the life is 380 hours for a color temperature of 3000°K (18 amps).[123] The 30-ampere lamp has a somewhat longer life, giving 100 hours of a color temperature of 3200°K.

The variation in brightness as a function of angle of view is shown in Figure 3.2 for tungsten and compared with Lambert's law.[67] This law states that at an angle θ to the normal, the brightness B_θ is given by

$$B_\theta = \frac{dI}{dS \cos\theta} = B_o$$

where dI is the luminous intensity, dS the surface area and B_o the brightness at $\theta = 0$. Figure 3.2 shows that Lambert's law is obeyed moderately well out to about 30°. The firgure also shows the polarization P, defined by

$$P = \frac{B_\perp - B_\parallel}{B_\perp + B_\parallel}$$

where $B_\perp$ and $B_\parallel$ are the brightnesses of the surface in terms of radiation polarized in a plane perpendicular to and normal to the surface, respectively. This property may be important for some purposes. The temperature distribution over the filament area has been given by Leighton[123] for General Electric lamps.

The standard tungsten lamp designed by the NBS is now manufactured by General Electric Company. The lamps may be obtained, for example, from

General Electric Company, Large Lamp Dept., Cleveland, Ohio
The Eppley Laboratory, New Port, Rhode Island

General Electric also supplies ribbon lamps other than type used as a standard.

3.3-2 Quartz - iodine lamp

This is a coiled filament tungsten lamp with a small amount of iodine inside the lamp bulb.[113,120] The iodine vapor returns evaporated tungsten from the bulb to the filament and permits operation at higher temperatures.[121] The quartz bulb is required in order to withstand the higher operating temperatures and also permit the source to be used in the ultraviolet. This lamp is manufactured by several companies for lighting purposes, e.g.,

1. General Electric Company, Large Lamp Dept.
   Cleveland, Ohio
2. Sylvania Electric Products Corp., Salem, Mass.
3. Westinghouse Electric Corp., Lamp Division
   Bloomfield, New Jersey

Various types of filament are available.

The National Bureau of Standards has selected the General Electric Lamp Model 6.6A/-T4Q 1 CL-200-W for use as an irradiance standard. At 6.6 amps. the life is 500 hours and calibration at 6.5 amps. gave a color temperature between 3000 and 3100°K, corresponding to a true temperature of around 3000°K. Such sources are an improvement over the tungsten filament sources when high irradiance is required, especially in the near ultraviolet. The spectral distribution may be affected by iodine when it is present in appreciable quantities as iodine absorbs in the green-yellow region of the spectrum.

3.4 Globar

This infrared source consists of a rod of bonded silicon carbide which is heated electrically by the passage of a current. Diameter is about 1/4 inch.

These sources are supplied by the manufacturers of spectroscopic instruments e.g.,

Perkin Elmer Corporation, Norwalk, Connecticut
The Warner and Swasey Co., Control Instrument Division, Flushing, New York

Globars can be made very stable: The Warner and Swasey Company, for example, uses feed-back control from the detected radiation output to achieve high stability. For their instrument the manufacturer quotes the following, using feed-back control from 1000°C to 1225°C,

i) Radiation intensity constant to within 0.1% of initial setting for 200 hours.
ii) Radiation intensity will return to within 0.1% of initial setting after turning off and on.

iii) Element temperature is stable to +2.5°C for line voltage changes of 110 to 120 volts A.C. and for cooling water temperature changes from 10°C to 30°C. Changes less than 0.5°C are normal.

The emissivity of the globar has been measured by Silverman.[70] The measurements were made on a tubular element at 1375°K. A typical maximum temperature of operation of a globar is 1175°K and the curve in Figure 5.3 is for this temperature, using Silverman's data.

Comparisons between the globar, zirconium arc and carbon arc are shown in Figure 5.3.

3.5 Nernst Glower

The Nernst glower[114] is a cylindrical rod or tube of refractory oxides (such as zirconia, yttria, thoria) with platinum leads at each end. The rod is non-conducting at room temperature and must be heated by an auxiliary source, which can be turned off when the glower is operating.

The radiation emitted peaks at 2,000 nm and the glower has been used as a source out to about 25,000 nm. It operates at a higher temperature than the Globar (1600-1700°K) but is fragile and less easy to use. It may be obtained from manufacturers of spectroscopic equipment e.g.

1. Beckmann Instruments Inc., Fullerton, California
2. Hilger and Watts Ltd., London, England
   (Engis Equipment Co., Chicago, Illinois)

A comparison in spectral output between the globar and Nernst Glower is given in reference (71). This shows that the Nernst Glower may be more intense than the Globar but the data given are insufficient for proper comparison.

3.6 Tungsten Glower

This is a source described by Taylor, Rupert and Strong[72] which is claimed by them to be superior in intensity to the globar and superior to the low temperature (3900°K) carbon arc for purposes where the absorption by CO_2 and H_2O is a problem.

The design of the source is fully described by these authors. A cavity is formed between two sheets of tungsten and heated to 3000°K at which temperature, if it is surrounded by an inert gas, the element may last many hours. The source constructed by these authors formed a cavity 1/4" x 0.040". No data were given on the uniformity.

Comparisons between this source, the carbon arc and the globar are shown in Figure 5.3. The extent to which this source is now used was not ascertained during the survey.

4. ELECTRIC DISCHARGE SOURCES

4.1 General

This heading covers a multitude of different types of light source which can be broadly classified into line and continuum sources. The former are by far the most numerous and also the least interesting for the purposes of this report. The continuum sources are very important for the vacuum ultraviolet and up to around 300 nm. They may have applications where compact or other arcs are unacceptable for some reason. Discussion of these sources is divided into two parts. The first deals with sources for the ultraviolet; it covers the continuum sources and also some line sources. Section 4.3 presents data on line sources; this is treated briefly since such sources are not of great consequence here. Lasers are discussed very briefly in Section 4.3-4.

4.2 Sources for the Ultraviolet

4.2-1 General

The general dearth of ultraviolet light sources combining high intensity and long life prompted an inquiry, more detailed than elsewhere in this survey, into sources constructed by various laboratories for their own use. Commercially available sources, and there are very few of them, have developed from laboratory light sources so that a scrutiny of the technical literature can often provide additional data on the source performance.

The frequency limitation (1 MHz) set in Part I of this study rules out normal A.C. excitation and also repetitive discharge sources. It does permit, however, consideration of excitation at radio and microwave frequencies. Such sources are very attractive since electrode evaporation, deposition and contamination are avoided. The importance of this lies in the fact that the appearance of contaminating material in the discharge, even in very small quantities, may substantially alter the spectral distribution of the emitted radiation, usually deleteriously, and that subsequent deposition of electrode material on the lamp window will reduce the output intensity.

Performance data on ultraviolet lamps, where available, were given in forms unsuitable for comparison with other types of sources and with the specifications set out in Part I (see Section 6). Intensity data were those detected at the exist slits of particular instruments. Data on uniformity of output were non-existent. In order to effect the comparisons made later in Section 7, the data obtained were manipulated freely with many assumptions; poor data were also included in some cases. Thus these comparisons between ultraviolet light sources should be treated as approximate only. The trouble lies largely in the fact that there is no standard source for the far ultraviolet, the tungsten lamp is very weak below 300 nm. Reviews of the sources for ultraviolet have been given by Koller[5] and Samson[7]: information has been drawn from these references in the following text.

4.2-2 Hydrogen continuum sources

The distinction between the light sources given here and those in Section 2.5 is a fine one. The hydrogen and deuterium sources described in that section also generate the well known hydrogen continuum, but are unsuitable for work much below 200 nm due to poor window transmittance and are of relatively low intensity. The sources described here represent the present limit in the technology of producing high intensity, stable and long life hydrogen continuum sources for the vacuum ultraviolet.

Hydrogen lamps emit a strong continuum which shows peaks at 188 and 240 nm. The extent of the continuum is from 168 nm below which there lies the intense molecular spectrum of hydrogen, to beyond 400 nm. The radiation originates through the transition of a hydrogen molecule from the stable $^3\Sigma_g^+$ state to the lower repulsive $^3\Sigma_u^+$ state. Therefore, efficient molecular recombination is a pre-requisite for high emission intensities. This may be improved by providing a metal surface, e.g., the Hanovia lamp uses a platinized capillary, although there is no universal agreement on the merit of this.[74]

Commercial hydrogen lamps for the vacuum ultraviolet (in addition to those listed in Section 2.5, which may be used down to about 165 nm when fitted with thin, high quality quartz windows), are available from the following manufacturers:

1. Engelhard Industries, Inc., Hanovia Lamp Division, Newark, N. J.
2. McPherson Instruments Corp., Acton Mass.
3. Tropel Inc., Fairport, New York

These three lamps differ from one another in important respects. Since data were difficult to obtain, several tests were run on the Hanovia and McPherson lamps and these revealed some of the problems in their use.

i) Hanovia Hydrogen Lamp

The Hanovia lamp appears to be a development of one constructed by Johnson, Watanabe and Tousey,[76] which was itself developed from one described by Powell. Their lamp, which was intended for D.C. operation, had a cathode which was 25 cm. in length; a water bath cooled the envelope around this end of the lamp. The lamp is constructed of fused quartz and is available with or without a window. In the filled version the windows may be ordinary fused quartz, suprasil or sapphire. The discharge passes through a platinized capillary, (4 mm bore and 11 inches long) and the electrodes are of high purity aluminum. The capillary is water cooled but the electrodes rely on radiation cooling; they are cylinders 4" long x 1 1/2" diameter and are a weak feature of the lamp.

The lamp is designed to be operated at up to one kilowatt on A.C. (0.52 amps. maximum) with a life around 100 hours at peak power. It can be operated on D.C. but experience at IIT Research Institute has shown a tendency for the electrodes to melt;[73] in some cases this occurred after only a short operating period at currents of 0.4 ampere. The McPherson Instrument Corp., which has been using these lamps, found that the windows blackened in a few hours at 500 watts D.C.[75]

In D.C. operation the cathode runs much hotter than the anode and appreciable evaporation and blackening of the envelope occurs at this end first; thus lamp life may be extended by having the cathode away from the viewing window. Nevertheless, one test in which the lamp was operated for over ten hours at 0.3 amp. D.C. (in four unequal periods), showed that instabilities started after about 9-10 hours.[73] These appeared visually as pulsations in lamp brightness at various low frequencies and were detected in the ultraviolet. The pulsations at first only lasted a few seconds but later became continuous. This condition defines the lamp life when good stability is required. The cause of these pulsations was not ascertained. (Forced air cooling was used on the envelope around the cathode during these tests).

When operated normally this lamp was quite stable, with a drift at 185 nm which was about 2% over a fifteen minute period (stabilized supply). Random fluctuations of about $\pm$ 2-4% were sometimes observed over short periods. Both these factors were sensitive to lamp age and to the time since start-up; the lamp always showed drift before it was properly warmed.[73]

This was the only filled lamp, operating at up to one Kwatt power, that was found to be available commercially. The short life is a drawback but lamps can be cleaned and refilled by the manufacturer. A D.C. power supply with a ripple of 0.1% was used in the above tests.

ii) McPherson Model 630 Lamp

This lamp is unfilled and can be operated with any "suitable" gas. It was originally designed by Hinteregger.[77] The electrodes are of aluminum and are connected by a 3 3/8" length capillary (6 mm bore is standard) which may be water cooled. One great advantage of this lamp is that it is easily disassembled for cleaning or replacement of defective components. The capillary, with water jacket, is sealed into the electrodes by means of O-rings. The cathode is in the form of a cavity with a large internal surface and no sharp edges; the outer surface has vanes for forced air cooling. The anode, which is designed to be attached directly to a monochromator is also water cooled. The lamp is designed for continuous operation at one Kwatt (electrical) and has been used in pulse applications at up to 8 Kwatt. The lamp is intended to be operated by flowing gas through it into the spectrograph; the makers supply a lithium fluoride window and bushing for use when this is undesirable the flow is then across the window.

Hexter[78] reports an increase of 60% in the output intensity when deuterium is used rather than hydrogen. This improvement is consistent with claims by the manufacturers of small hydrogen arc lamps (Section 2-5), who quote even higher gains.

Tests on the stability of the lamp made at IIT Research Institute showed this to be $\pm$ 1/2% for short term (periods around 0.3 second) with a drift over a ten minute period of <2%. Fluctuations at frequencies up to 100 Hz were of the order 1/2 to 1% (peak to peak) of the lamp signal, higher frequencies were not monitored.

Figure 4.1 shows a comparison between the Hanovia and McPherson lamps.[73] The Hanovia lamp was factory filled and had a suprasil window. Radiation from the McPherson lamp passed through a suprasil window placed 2.8" from the end of the capillary. Hydrogen was flowed through the McPherson lamp during the experiments. The experimental arrangement used in this comparison was

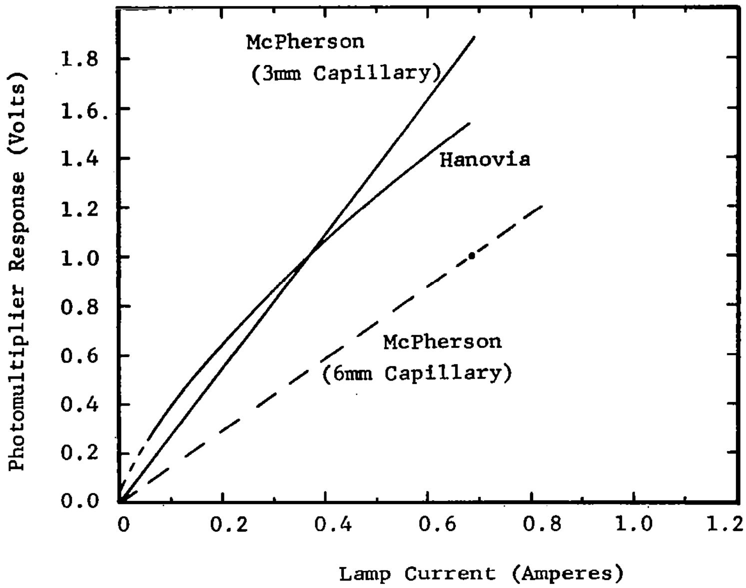

Figure 4.1 Relative Performance of Hanovia and McPherson Lamps at 185 nm. Both had Suprasil Windows.

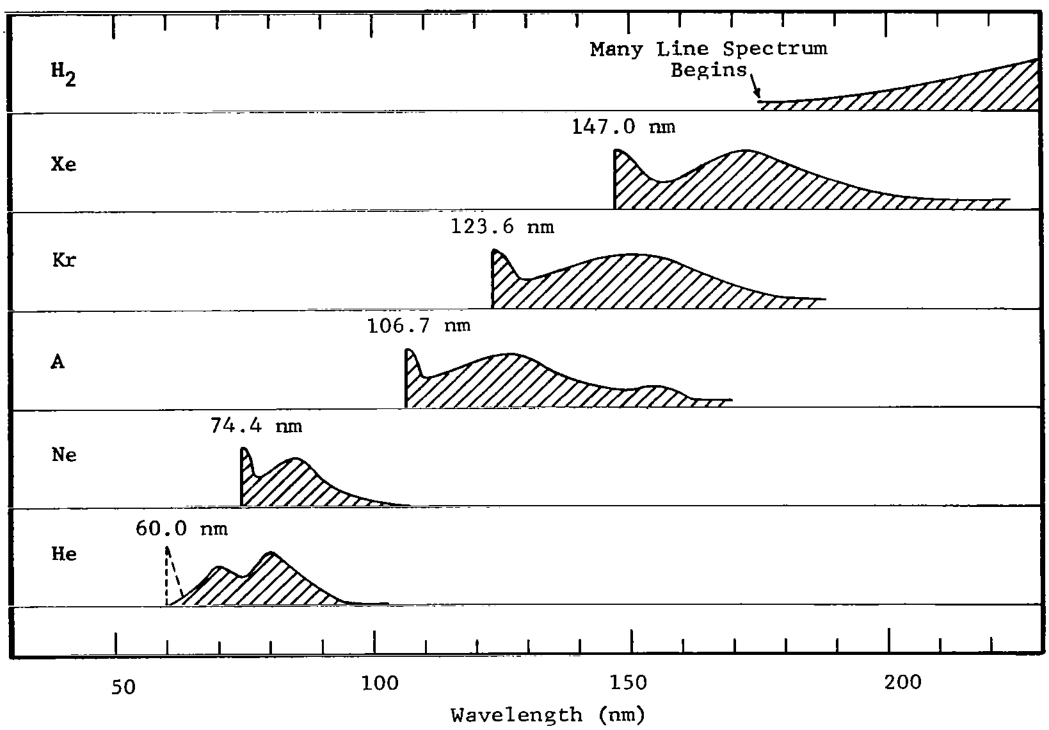

Figure 4.2 Rare Gas Continua[84]

such that the ends of the capillaries of the two lamps were at almost the same distance away from the monochromator slits and the solid angles subtended by the monochromator at the ends of the capillaries were nearly equal. For intensity comparisons a correction factor was applied to one lamp's data, this compounded the slight differences in distance of the capillaries from the monochromator and the slightly different light collection angles.

An experiment made in this manner does not necessarily compare the maximum intensities. The capillary of the McPherson lamp was lined up along the optical axis but the line-up of the Hanovia was different since the end window was not quite perpendicular to the capillary. A second point is that radiation from the fringes of the discharge is excluded. Other tests on the Hanovia lamp showed that, at 200 nm, the highest intensities were obtained by displacing the lamp off axis and tilting it. The maximum was 1.6 times that observed when the lamp was lined up. Thus, the results of the comparison between the two lamps are subjected to these uncertainties.

The above experience shows that these two lamps have different advantages. For power levels up to about 700 watts D.C. the outputs are comparable (with the non-standard 3 mm capillary in the McPherson lamp) and the Hanovia lamp has the advantage of requiring power and water cooling only. For higher D.C. power levels the Hanovia lamp is unsatisfactory and the McPherson lamp should be used, with the additional requirements of vacuum and gas handling systems.

The power supply that was used did not allow currents higher than 0.65 amperes to be passed through these lamps but the McPherson lamp is made to run satisfactorily at one ampere, and may take more. Samson[74] and Huffman[116] found that intensities increased nearly linearly with current in hydrogen discharge lamps.

iii) Tropel BNH-1 Discharge Lamp

This lamp is smaller and operates at a lower power (360 watts D.C.) than either of the above two lamps. It has no window and is intended to be used with a differential pumping chamber and flowing gas.

The lamp has a 2-inch long capillary of boron nitride, which is made in two sections. Water cooling is provided for the capillary only, but since the aluminum electrode is screwed into the boron nitride (a wider section) it would also benefit; the only other cooling provided is by the flowing gas.

The manufacturer was unable to supply performance data for the lamp, except for the obtainable intensity at Lyman-α 2×10^{12} photons sec^{-1} mm^{-2} measured at the exit slit of the Tropel Model N-2 monochromator (0.4 meter). In addition, Smith[79] quoted the ratio of the intensities of the Lyman-α to the molecular line at 160.8 nm as ten for the Tropel and one for the Hanovia lamp.

The lamp operates at a pressure of 1 torr, measured in the Tropel differential pumping chamber, and is unstable at higher pressures.[79] The Tropel power supply has a ripple of 1-2 per cent.

iv) Other Types of Hydrogen Lamps

These are not commercially available and were constructed in individual laboratories. Samson[7] describes a source designed by Hunter which he has found very satisfactory. The source consists of a 4" quartz disc with a 4 mm bore capillary sealed into the disc through its center and normal to its surface. The electrodes are cylinders which seal onto the quartz disc with O-rings. The cathode is water cooled and the anode flange bolts directly to a monochromator. Samson has found this lamp to be very rugged and easily stabilized in the glow discharge region; at higher currents, current stabilization is required. This lamp differs from all those described above in that the capillary is not cooled and runs hot.

The use of heated cathode hydrogen discharge lamps has been described in the literature by Johnson[32] and Hartman[80]. This type of source was discussed by Samson in his review[7] with special reference to the Hartman type of source.

The Hartman lamp[80] employes a nickel ribbon coated with strontium and barium carbonates, requiring 20 to 25 amps for heating. The anode is water cooled copper. The lamp is ignited with a Tesla coil and runs at 60-90 volts depending on age, with a current of around 2.5 amps. It has a quartz capillary 3/8" in diameter, with an orifice through the anode of about 1/8" diameter. In operation the lamp stability was reported to be good. From the geometry it is apparent that the emitted radiation will be confined to a comparatively narrow angle. Samson reports that the intensity in hydrogen discharges is greater by a factor 2 or 3 than that produced by the cold cathode discharge.

Warneck[81] has described a microwave powered hydrogen source. This utilizes a Raytheon 125-watt Microtherm Unit. The radiation output includes both molecular lines and continuum; the relative strength of the Lyman-α line (121.6 nm) and the molecular lines is determined by the pressure and method of excitation.

4.2-3 Rare gas continua

Radiation from rare gas discharges has received much study during the past fifteen years and is now used extensively for ultraviolet light sources. Three methods of excitation have received most attention:

(a) A.C. and D.C. discharges[82]

(b) Condensed discharges[83,84]

(c) Microwave discharges

Figure 4.2 shows a schematic representation of the rare gas continua produced by uncondensed discharges.[84] Through the use of repetitive condensed discharges important new rare gas continua have been obtained.[4,83,86] First discovered in helium,[88] which was found to have a new continuum stretching from around 105 nm to beyond 400 nm with a peak around 250 nm, these continua are excited by self-triggered condensed discharges at high pressures (400-800 torr) and the McPherson Model 630 lamp has been used for this purpose. The new rare gas continua at long wavelengths only appeared if the condensed discharge was self-triggered.[4] Similar continua have been detected in neon, argon and xenon.[89] These discharges have been operated at frequencies up to about 1600 Hz which is too low to meet the requirements listed in Part I. They remain of interest however, and may later be obtained at higher frequencies. The high pressure helium continuum is shown in Figure 4.3 as measured at the exit slit of a monochromator.

Tanaka[90] has studied discharges in mixtures of rare gases in the hope that their combined continua may be observed, thus extending the range of the sources and decreasing the intensity slopes. He found that only one gas was excited, that with the lowest excitation energy. He obtained a combination of the spectra by having two tubes, each filled with one rare gas. These were placed end to end so that emission from both entered the spectrograph.

Microwaves have been used to excite the rare gas continua and such sources are available commercially. Wilkinson and Byram[91] have recently given a good review of the operation and performance of these sources. A number of lines are observed with these continua, mostly belonging to impurities such as carbon, nitrogen, etc., but the gas resonance lines are also excited.

The source generally used consists of a quartz or pyrex tube of about 1/2 inch diameter which passes through a microwave cavity. A window, usually of LiF, may be used to seal the end: a side arm contains a getter. Most of the work reported has been performed using a Raytheon Diathermy unit operating at 2450 MHz at 125 watts but others have also been used.[91] The method of construction of these lamps is described by Wilkinson and Byram: rare gas pressures are in the region of 200 torr. Several kinds of microwave cavities have been tried and are described and discussed by Fehsenfeld, Evenson, and Broida,[92] for a frequency of 2450 MHz.

The relative intensities of the rare gas continua that are achieved are shown in Figure 4.4[91] in which corrections have been applied for the transmission of LiF and the reflectivity of the grating.

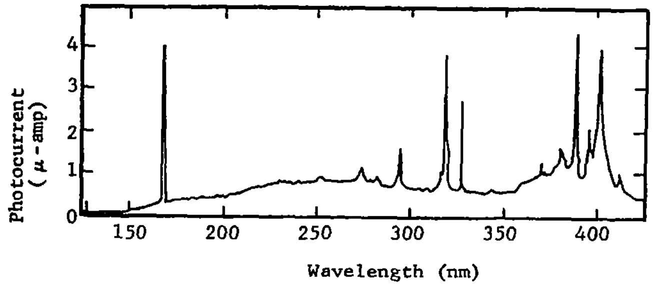

Figure 4.3 Spectrum from High Pressure Helium (600 Torr), Self Triggered, Condensed Discharge[4]

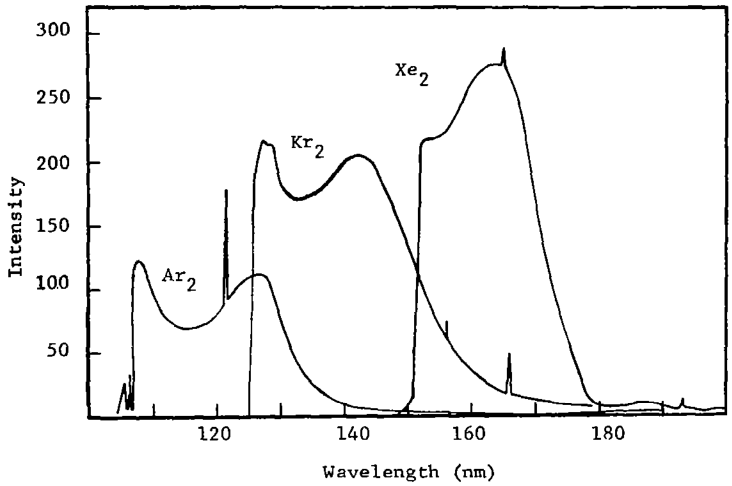

Figure 4.4 Rare Gas Continua Excited in Microwave Discharges[101]

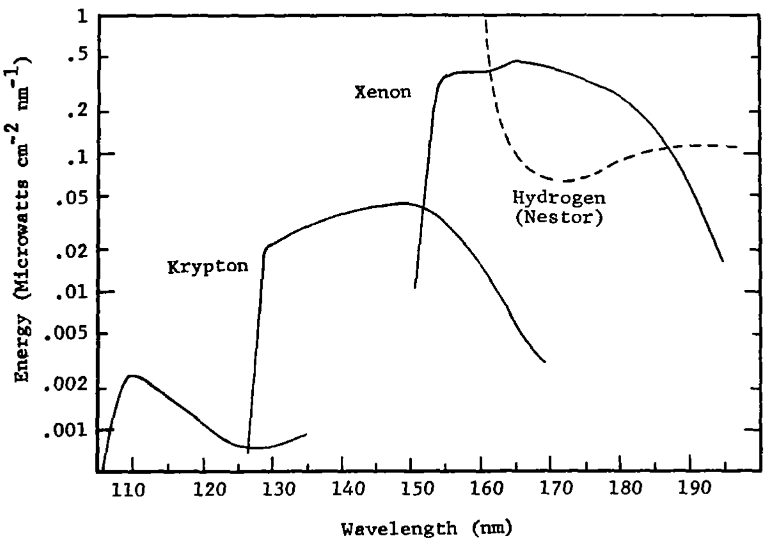

Figure 4.5 Rare Gase Continua Excited in Jarrell-Ash Microwave Discharge Lamps (Jarrell-Ash Literature)

These sources are available commercially from the following manufacturers:

1. GBL Associates Inc., Alexandria, Virginia (literature not studied)
2. Jarrell-Ash Company, Waltham, Massachusetts
3. S. J. Industries, Alexandria, Virginia
4. Spex Industries, Inc., Metuchen, New Jersey

The Jarrell-Ash Company and S. J. Industries, supply sealed and filled lamps. S. J. Industries and Spex Industries supply components. The relative energy distribution at the exit slit of the monochromator is shown in Figure 4.5, taken from the Jarrell-Ash literature. The area referred to is that of the exit slit of a 1-meter Seya-Namioka monochromator. The output of the Nester hydrogen lamp is shown for comparison and this was calibrated in absolute terms. Jarrell-Ash quotes a ripple of less than $\pm$ 1% and a life of 500 hours for their sources, which operate at the usual 2450 MHz and 200 watts maximum.

Wilkinson and Byram quote a drift rate of 1 per cent per hour. Intensity loss is due to a brown deposit which forms on the LiF window, which may be removed by polishing; this deposit was attributed by these authors to residual organic material in the discharge tube.

The output intensity increases nearly linearly with power

(Wilkinson and Byram show this for krypton up to 100 watts[91]) and power levels of 900 and 1000 watts can be used,[91,93,94] although heating of the tube and window sealing becomes a problem.[94]

4.2-4 Line sources

The sources constructed have mostly been for the region below 150 nm, using the hydrogen Lyman-α 121.6 nm or rare gas resonance lines, the highest being xenon at 147 nm, which has been generated at high intensities in microwave discharge sources. These sources operate at low pressures, appreciably lower than 1 torr. The effect of increasing power in such sources is probably much greater than for the continua, where self-absorption becomes apparent,[91] and Schlag has found that by raising the power from 150 to 1000 watts the Xe resonance line intensity increases by a factor 10-50.[94]

Okabe excited a mixture of 20 percent nitrogen in argon[95] and obtained intense lines in the regions 149.3-149.5 nm and 174.3 to 174.5 nm. He reported an average life of 10 hours for his rare gas lamps but Schlag has found that they are good for 1000 hours,[94] at which time the intensity had fallen slightly.

The mercury resonance lines at 184.9 and 253.7 nm have been excited strongly in many lamps, the compact arc (Section 2.2) generates these but relatively weakly and the lines are broadened. A discussion of the available mercury lamps is postponed to

Section 4.3-2.

Hollow cathode lamps can be used to excite lines in the ultraviolet and the design of such a lamp (Schuler lamp) has been described by Newburgh, Heroux and Hinteregger.[83] The lamp was intended for use at shorter wavelengths than those of concern here but may have application above 150 nm.

4.3 Line Sources

4.3-1 General

With the exception of lasers, line sources are of less interest in the present context than continuum sources and so are treated rather briefly. An exception to this statement is to be found in the ultraviolet, where sources are generally weak. Mention has already been made of microwave excited line sources (Section 4.2-4).

The number of wavelengths for which commerical lasers are available is a small fraction of the total number at which laser action has been observed in research laboratories. Mention is made in Section 4.3-3 of lasers commercially available, but for details of lines which have been observed and the characteristics of the radiation the literature must be consulted.

4.3-2 Mercury sources

These find many applications in research and industry and are widely produced. Companies which manufacture such sources are:

1. Beckman Instruments, Inc., Fullerton, California
2. Black Light Eastern, Westbury, New York
3. Engelhard Hanovia Inc. (Hanovia Lamp Div.) Newark, New Jersey
4. Gaertner Scientific Corp., Chicago, Illinois
5. General Electric Corp., (Large Lamp Div.) Cleveland, Ohio
6. Hilger and Watts Ltd., London, U.K. (Engis Equipment Co., Chicago, Illinois)
7. Klinger Scientific Apparatus Corp., Jamaica, New York
8. Orion Optics Corp., Stamford, Connecticut
9. Osram Gmbh, Germany (Macbeth Sales Corp., Newburgh, N.Y.)
10. Ultraviolet Products Inc., San Gabriel, California
11. Westinghouse Electric Corp. (Lamp Division) Bloomfield, New Jersey

There are other suppliers of the lamps, e.g. the various manufacturers of general laboratory apparatus and equipment.

The mercury lamps made by General Electric and Westinghouse are primarily for lighting purposes. They also make germicidal lamps which are strong sources of 253.7 nm radiation. Engelhard-Hanovia markets two sources, both primarily of 253.7 nm radiation, types 735A-7 and SC-2537. The former is intended for general laboratory use but the latter was specifically designed for photochemical applications and the actual emitting area is large. The emission at 184.9 nm is only 2% that at 253.7 nm for both the Hanovia sources.

Black Light Eastern, Orion Optics, and Ultraviolet Projects manufacture similar lamps to one another which can be obtained with suprasil envelopes to reduce absorption of the 184.9 nm radiation. The relative intensity of the spectral lines can be adjusted somewhat since raising the current depletes the fraction radiated at 253.7 nm. The output at 184.9 nm can be enhanced by over a factor ten by cooling the envelope with an air jet. These lamps have a very long life: Ultraviolet Products report a test in which lamps were run continuously for over 3 years before failure.

Lamps are normally supplied with A.C. power supplies but can be operated satisfactorily on D.C.

Barnes[96] reports on a study of the absolute emission intensities of low-pressure mercury vapor lamps with various rare gases (normal fills contain a rare gas). He found that the 184.9 nm radiation was 12-34 per cent of that at 253.7 nm. The absolute intensities varied with the bulb wall temperature, fill pressure, current, and type of gas fill. The maximum values reported in this paper were

for λ = 253.7 nm $\quad$ 12.5×10^{-3} watt sterad^{-1} cm^{-2}

λ = 184.9 nm $\quad$ 3.94×10^{-3} watt sterad^{-1} cm^{-2}

and these were for different operating conditions; the area applies to area of tube wall and the measurements were made normal to the discharge tube.

The Black Light Eastern source has been studied by Childs,[9] who was investigating the use of this lamp as a calibrated source of 253.7 nm radiation. He found that 92 per cent of the radiation was concentrated at 253.7 nm.

These sources are available in electrodeless form, e.g. Hilger and Watts manufactures a Mercury-198 isotope source which is excited in a microwave discharge.

4.3-3 Miscellaneous line sources

There are a large number of these available commercially and only brief mention is made here. Typical manufacturers are those listed in Section 4.3-2.

Hollow cathode sources are widely used in atomic absorption spectroscopy and these are manufactured by Hilger and Watts Ltd., and by Westinghouse Electric Corporation (Electronic Tube Division), for example. These sources use a discharge in a rare gas to excite lines of the cathode material. The intensity of the metal lines, and the presence of rare gas lines in the same region, depend on the nature of the gas fill. Westinghouse can provide sources with a wide range of cathode materials and their literature should be consulted for details. The life of such tubes depends on the gas fill and cathode material; it is dictated by the rate of deposition of sputtered cathode material on the window and on the rate absorption of the gas fill by the sputtered material. Life is several hundred hours and often exceeds 1000, depending on type.

Crosswhite, Dieke and Leganeur[115] studied a hollow cathode with iron electrodes. The intensities of the iron lines were greatest with a helium fill and, when operated at 400 ma, the lamp gave line intensities which were approximately 10 times weaker than those produced in an iron arc at 2.2 amperes.

The hollow cathode source is very stable. Crosswhite et al.[115] did not find any intensity fluctuations over periods of days - such fluctuations as they did observe were attributable to the detecting photomultiplier.

Discharge lamps with various gas fills are available from many manufacturers. Black Light Eastern, in their Spectroline series, offers

Cd, Cs, He, Hg, Hg-Cd, K, Na, Ne, Rb, Tl, Zn

In addition to these, Hilger and Watts Ltd., (Engis Equipment Co.) supplies

Ar, Hg(low or high pressure), Hg-Cd-Zn, In, Kr, Xe

The Hilger lamps are manufactured by Philips Gmbh of Germany. Some of these lamps, also made by Philips, are supplied by Klinger Scientific Apparatus Corp.

Electrodeless discharge lamps have been constructed for the excitation of vapors. Zelikoff, Wyckoff, Aschenbrand and Loomis[99] used microwaves at 2450 MHz to excite metal vapors. They obtained lines from 225 up to 410 nm. Radio frequency excitation of potassium and rubidium lines has been described by Atkinson, Chapman and Krause[100], who obtained higher intensities (about a factor two) than those given with the more conventional discharge lamps. Powell, Fletcher and Lippincott[107,108] have described a high intensity radio frequency discharge operating at about 5 MHz; they excited lines of Hg, K, Rb, Cd, He, Cs, and Tl. Mavrodineanu and Hughes[101,102] have published spectra obtained with radio frequency discharges using powers up to 2 kilowatts at 2450 MHz. These papers give extensive lists of references to such work and include a very large number of spectral lines in the range 220 to 800 nm.

4.3-4 Lasers

Lasers are the most intense sources of radiation available and their characteristics are unique. This section presents only the data available from commercial suppliers. Details of laser characteristics, especially the important ones of beam uniformity and spectral characteristics of the emitted radiation have been omitted; reference should be made to the pertinent technical literature, e.g. Birnbaum,[103] Bloom,[117] Snitzer,[118] Kiss and Pressley.[119]

The number of spectral lines for which laser action has been obtained is vastly greater than those available commercially. Bennett[104,105] lists lines observed up to 1965.

Pulsed lasers are excluded from this survey. This leaves gas lasers as the primary commercially available sources for CW operation. Other CW lasers are the neodymium glass laser and semiconductor diode lasers.

Information on their laser products was obtained from the following companies:

1. American Optical Co. (Space Defense Division) Southbridge, Mass.
2. Applied Lasers, Inc., Stoneham, Mass.
3. Coherent Radiation Labs. Inc., Palo Alto, California
4. Electro-Optics Associates, Palo Alto, California
5. General Electric Company (Semiconductor Products Dept.), Syracuse, N. Y.
6. h nu Systems, Inc., Palo Alto, California
7. Hughes Research Laboratories, Malibu, California
8. Korad Corp., Santa Monica, California
9. Maser Optics, Inc., Boston, Mass.
10. Optics Technology, Inc., Palo Alto, California
11. Perkin Elmer Corp. (Electronic Products Division) Norwalk, Connecticut
12. Philco (Lansdale Division), Lansdale, Pa.
13. Raytheon Co. (Microwave and Power Tube Division) Waltham, Mass.
14. Spectra-Physics, Inc., Mountain View, California
15. Watkins Johnson Co., Palo Alto, California

Table X summarizes the data on CW gas lasers obtained from the manufacturers; data on semiconductor lasers is shown in Table XI. The semiconductor lasers have to be operated at

TABLE X CW GAS LASERS

TYPE	LINES (nm)	POWER RANGE MILLIWATT	SUPPLIERS
He-Ne	632.8, 1152.3, 3391.2	0.1 to 200	American Optical Co. Electro-Optics Associates h-nu Hughes Maser Optics Optics Technology Perkin Elmer Raytheon Spectra Physics Watkins Johnson
Ar	457.9, 465.8, 472.7, 476.5, 488.0, 496.5 501.7, 514.5	100 to 5000	Applied Lasers Inc. h-nu Raytheon
Kr	520.8, 530.9, 568.2, 647.1, 657.0, 676.4, 687.1	2500	h-nu
Xe	541.9, 597.1, 627.1	500	h-nu
CO_2	10600	10 to 2×10^4	Coherent Radiation Labs. Perkin Elmer Raytheon
N_2O	5000		Perkin Elmer

TABLE XI SEMICONDUCTOR LASERS

Manufacturer	Type	Model	λ (nm)	Power Milliwatts	Emitting Area μ^2	Line Width (A)
General Electric	Ga-As	H2A1	8420	500	10 x 200	0.001
		H2A2	8420	150	10 x 200	
		H2A3	8420	1250	10 x 200	
		H2A4	8420	2250	10 x 200	
Raytheon	Ga-As	RSL-4	8400	500		.02 per mole

TABLE XI-A CW INFRARED EMITTING DIODES

MANUFACTURER	TYPE	MODEL	λ (nm)	POWER MILLI-WATTS	EMITTING AREA	LINE WIDTH (Å)	OPERATING TEMPERATURE
General Electric	Ga-As	LED-5	910	10		210	25°C
			8425	500		175	77°K
Philco	Ga-As	GAE-402	900	0.09	0.030" dia.	200	300°K
	Ga-As	GAE-404	900	0.45	0.030" dia.	200	
	In-As	IAE-602	3,900	0.01	0.030" dia.	900	300°K
Raytheon	Ga-As	RSE-1	900	0.07	1 mm^2	550	25°C
			840	3		250	77°K
Texas Instruments	In-As		3000-3900				77°K
	Ga-As	TIXL01	900	0.05		250	25°C
	Ga-As	TIXL02	900	0.09		250	25°C
	Ga-As	TIXL03	920	20			25°C
	Ga-As	PEX1201	900	0.8			25°C

TABLE XII CW CRYSTAL LASERS

MANUFACTURER	TYPE	MODEL	λ (nm)	POWER MILLIWATT
Korad	YAG (1)	KY-1	1064.8	500
Raytheon	YAG	YAG	1064.8	1000
	Calcium (2) Tungstate		1058	100

(1) Neodymium doped - yttrium aluminum garnet

(2) $Ca\ WO_4$: Nd^{+++}

low temperature, e.g. the General Electric H2A series was designed for operation at 4°K but can be operated up to 50°K with reduced output. Some infrared emitting diodes have been listed in Table XIa since these sources are not covered elsewhere in this report.

Only two crystal lasers appear to be available commercially, these are listed in Table XII.

The manufacturers are able to supply a certain amount of data on performance, intensity and wavelength drift, beam uniformity, noise, etc. These are very important and should be studied carefully before making a selection for stringent operating conditions. For example, Perkin-Elmer states that He-Ne lasers have a frequency modulation of about one per cent at 140-200 KHz. Also, the Spectra-Physics literature shows a photograph of the intensity output across the beam of a He-Ne laser, suggesting that noise in the output is quite nonuniform in spatial distribution.

5. INTENSITY COMPARISONS BETWEEN SOURCES

These results are presented in Figures 5.1, 5.2 and 5.3. Such comparisons are not strictly valid in all cases but the data have been presented in this manner to give an order of magnitude comparison between the various sources. The weakness of the ultraviolet sources is readily apparent; since many detectors respond to individual photons these curves could have been presented with the intensities given in quanta sec^{-1}, which would have shown the ultraviolet sources to be weaker still.

Figure 5.1 presents data which were deduced from several sources. The resulting curves are very approximate in the cases of the discharge lamps. Baum and Dunkelman[106] present data for the Hanovia lamp (still essentially the same lamp) down to 240 nm and also for the Nestor lamp. Source curves obtained for the Hanovia lamp at IIT Research Institute were matched into the curve of Baum and Dunkelman at the peak, making corrections for photomultiplier response and grating efficiency. An approximate calibration of the lamp at IIT Research Institute showed lower intensity figures by a factor of about five, but the operating conditions and assumed emitting area of the lamp may be different, Baum and Dunkelman do not give details of these. The Jarrell-Ash data were related to the Hanovia lamp via the company literature which shows a comparison with a Nestor arc, which is also given by Baum and Dunkelman. The curves for the xenon and carbon arcs

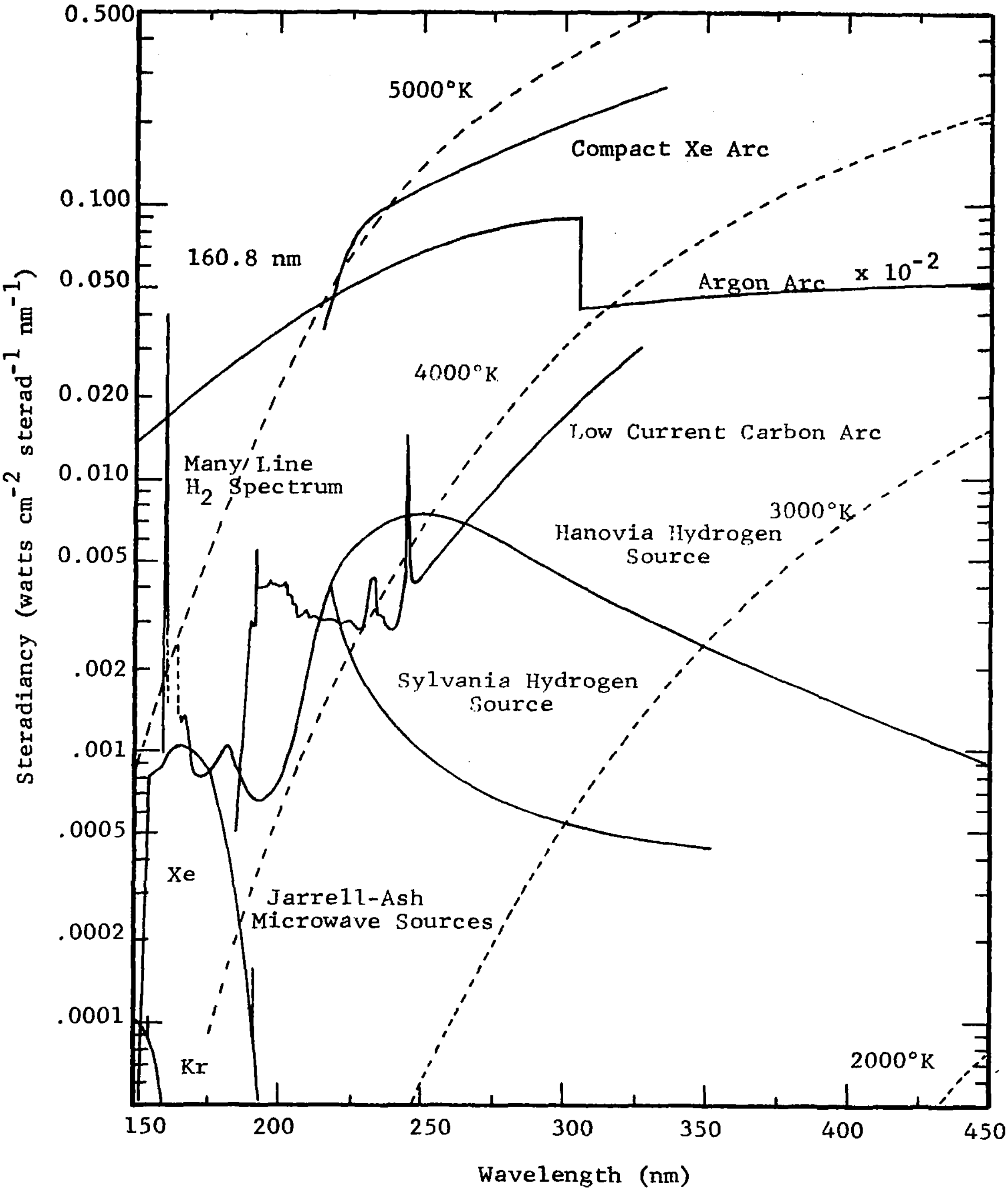

Figure 5.1 Comparison of Spectral Steradiances for Ultraviolet Sources. ----- Blackbody Curves

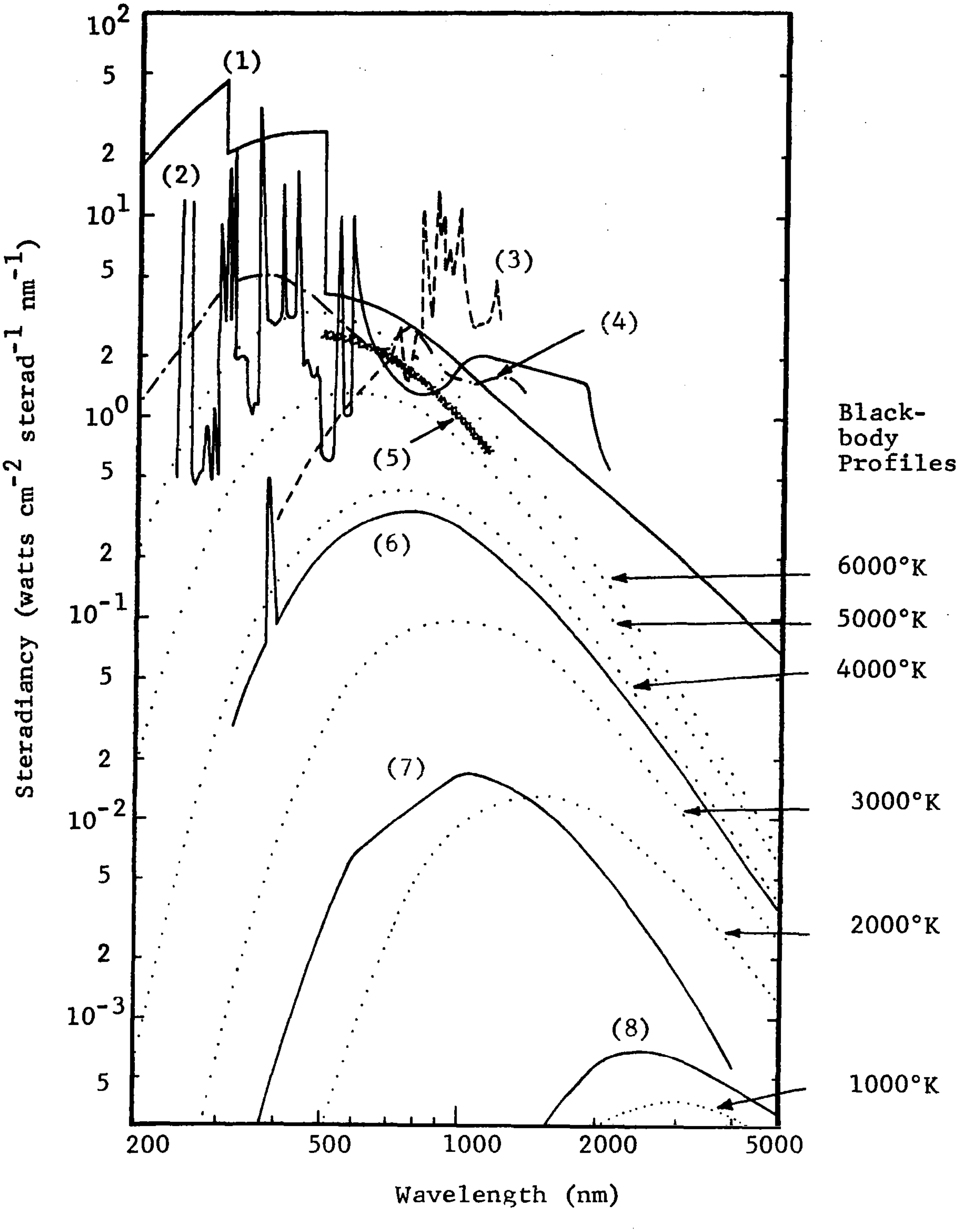

Figure 5.2 Intensities of Light Source for the Visible and Near Visible

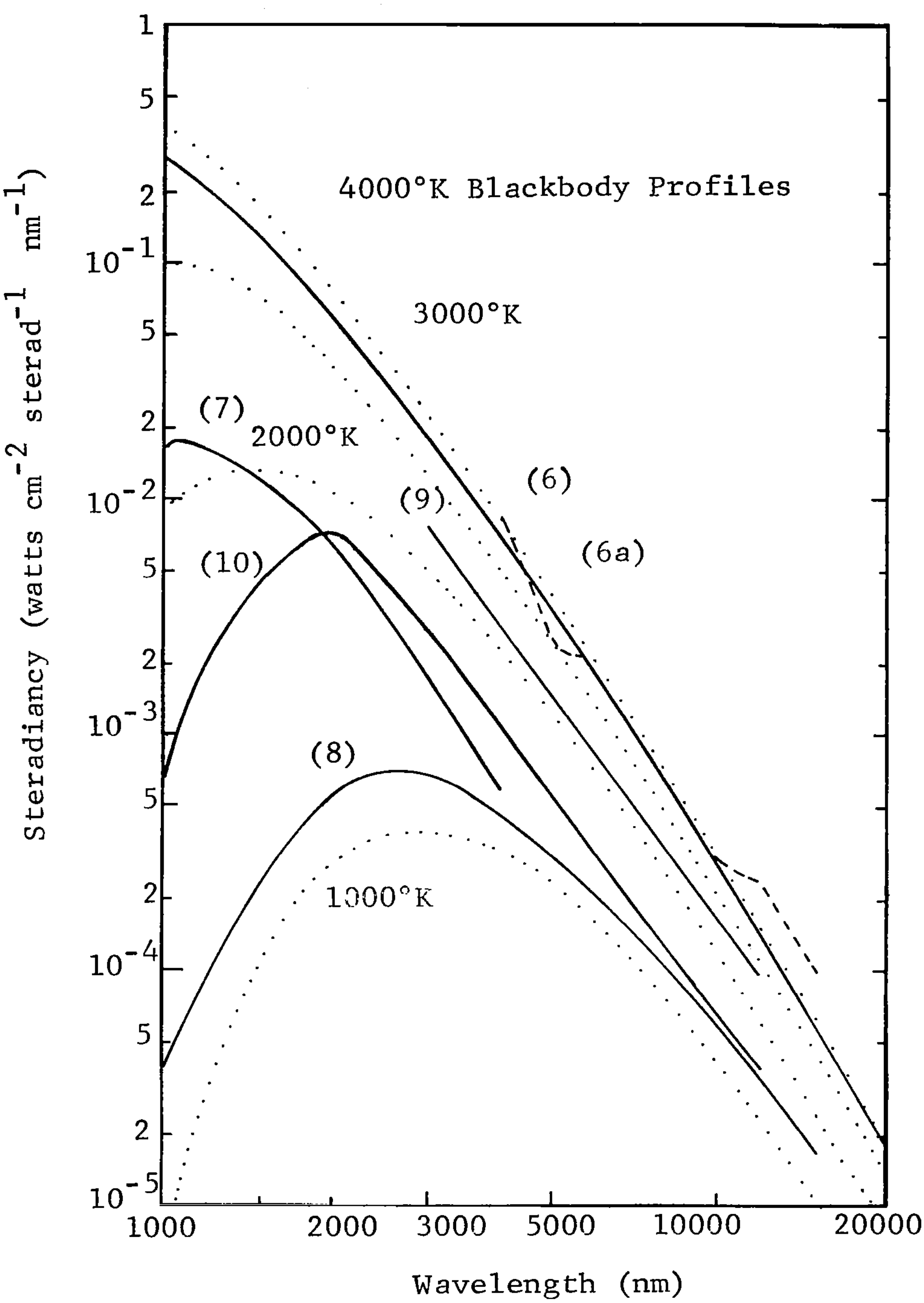

Figure 5.3 Intensities of Light Source for the Infrared

are those given by these authors,[106] but the carbon arc data were also matched into that given by Johnson[40] -- see Figure 2.20. The argon arc is shown multiplied by a factor 10^{-2} in order to present it on the figure; this curve was calculated in Appendix A and is only approximate, it takes no account of self-absorption which may reduce the intensity drastically.

The light source numbers referred to in Figures 5.2 and 5.3 are:

1. Argon arc continuum - approximate calculation excluding effects of self-absorption (see Appendix)
2. Mercury compact arc PEK 110
3. Xenon compact arc PEK X75
4. Giannini vortex stabilized radiation source
5. High current carbon arc (brightness temperature of 5800°K)
6. Low current carbon arc

6a. Measurements of Rupert and Strong

7. Tungsten ribbon filament lamp (at 2600°K)
8. Globar at 1175°K
9. Tungsten glower
10. Zirconium arc

Figure 5.2 shows the relative intensities of sources available in the visible and near visible regions. The compact arc data were taken from the PEK literature assuming emission over the areas given in Table IIC. Appreciably higher steradiancies would be obtained from the brighter regions. Finkelnberg and Latil did not give a spectral distribution for the higher current carbon arc but said that the radiation followed a blackbody of 5800°K, hence a portion of this curve is added; considerable radiation from the flame is to be expected, probably giving strong CN and C_2 bands, which are not shown in the figure. The steradiancy of the Giannini vortex stabilized arc is also shown, taken from Figure 2.35 and assuming the area given there; this too is much more intense near the cathode and on the axis, see Figures 2.37 and 2.38.

Infrared sources are shown in Figure 5.3. The Nernst glower was omitted for lack of suitable data (this may be taken as slightly more intense than the Globar except at around 1000 nm where it is much greater). Data for the various arcs were obtained in the literature as described in the foregoing sections. The argon arc data were calculated in Appendix A. The high pressure mercury and xenon compact arcs cut off at 2500 nm due to the quartz envelope; a crystal window might be made to withstand these pressures, and so extend the useful range of these lamps, but this has not yet been done apparently; if it were, the xenon continuum would probably provide a useful infrared source.

6. SOURCE PERFORMANCE: COMPARISON WITH THE SPECIFIED REQUIREMENTS

The source requirements for light sources to be used in a crossed beam remote sensing system are[1]:

Spectral Range	150-2000 nm
Spectral Radiance	
I_λ (watts/sq.cm./sterad/ μ)	High as possible with spectral bandwidth $\frac{\lambda}{\Delta\lambda} < 1000$; required as a function of wavelength, angle and of position over source.
Area (sq. cm.) (Implies uniformity condition)	Definition: Area over which brightness varies by $\leq \pm$ 5%.
Random Fluctuations	$< \pm$ 1% over 10 minutes
Drift (Long term)	< 5% over 5 minutes
Ripple	< 0.1%
Lifetime	> 5 hours
Mode	D. C. or frequencies > 1 MHz

In some cases it was possible to evaluate the performance of light sources in terms of these requirements, in others estimates could be made. A summary of such data is presented in Table XIII.

TABLE XIII

SOURCE PERFORMANCE

	Useful Spectral Range (nm)	Uniformity		Stability			Life
		Area mm dia	Angle Cone	Random Fluctuations	Drift	Ripple	
Compact Arc - Hg	220 - 2,500	0.8[1]	20° [2]	[3]		Yes	Yes
Compact Arc - Xe	220 - 2,500			(No)	(Yes)	Yes	Yes
Carbon Arc (Low Current)	250 - 20,000	4	(30°)	Yes	Yes	Yes	Yes
Carbon Arc (High Current)	(250 - 20,000)	3	(30°)	(No)	(No)	(Yes)	
Zirconium Arc	400 - 14,000	1	35°	(Yes)	Yes[4]	(Yes)	Yes
Hydrogen Arc (Compact)	200 - 400	(1)	(30°)	Yes	(Yes)	Yes	Yes
Argon Arc[8]	(150 - 20,000)	(1)		(Yes)	Yes	Yes	Yes
Vortex Stabilized Argon Arc	200 - 2,500	(1)[5]	70°	(No)	(No)	No	Yes
Blackbody Sources	300 - 10,000	6[6]	30°[6]	Yes	Yes	Yes	Yes
Tungsten Lamp	300 - 2,500	2	65°	Yes	Yes	Yes	Yes
Globar	1,000 - 20,000	4	(60°)	Yes	Yes	Yes	Yes
Nernst Glower[7]	1,000 - 20,000						
Tungsten Glower[8]	1,000 - 15,000						
Rare Gas UV Sources	150 - 180				Yes	Yes	Yes
Hydrogen UV Source	150 - 300	(2)	(5-10°)	Yes	Yes	Yes	Yes

Uniformity - Area giving brightness variations $< \pm 5\%$
Angle giving brightness variations $< \pm 5\%$

Stability - Random Fluctuations $< \pm 1\%$
Drift $< 5\%$ over 5 minutes
Ripple $< 0.1\%$
Life > 5 hours

1. Varies very considerable depending on lamp and region. These figures are from Figure 2.7 Curve B. Electrode design can improve this but also the most intense lamps - e.g. Hanovia 959C - are much less uniform.

2. Some are less and some may be more (notably A.C. arcs).

3. Probably more stable than the xenon arcs.

4. But compare Figure 2.28 and comments in the text of Section 2.4 (Part II).

5. This source has much greater uniformity along the arc and may fulfill the requirements for a length of 3 to 4 mm.

6. Varies considerably, see text and Tables VIII and IX.

7. Data on this source was found difficult to obtain. Texts on infrared technology yielded little and likewise the manufacturer's literature.

8. Not available commercially.

There are several ambiguities in such a compilation; for example the uniformity of a source depends on the spectral region, region viewed and also on the direction relative to a source axis. Some comments follow after the table according to the indicated numbers. Where a blank occurs no data were available and it was not possible to make a useful estimate. Figures in parenthesis are considered more uncertain than the others. The spectral sterandiancies were shown in Figures 5.1 to 5.3.

Line sources are omitted from Table XIII as these were not studied in much detail. For the wavelengths at which they emit, line discharge sources may have better stability than other types of similar intensities because the overall power dissipation is often smaller.

The characteristics portrayed in Table XIII do not necessarily follow from the same lamp. For example a compact arc may be chosen for optimum uniformity over a large emitting area, or for a wide angle in a particular direction (the words 'large' and 'wide' are relative), one lamp is unlikely to give both. The figures mentioned in the table are those that can be achieved, but many types of lamp (e.g. types of compact arc) may not achieve these and special selection for a particular application is essential.

The concurrence with specifications of the random noise from light sources is very uncertain. The data entered in

Table XIII follow from the literature, manufacturers data and in some cases from data communicated privately. This survey is concerned with the frequency range 0-1 MHz, and it is fairly certain that these fluctuations have not been measured over this whole range. Consequently it would be wrong to take these entries too seriously.

The useful spectral range has been decided rather arbitrarily. Thus, Figure 5.1 shows that the carbon arc emits more strongly than the Hanovia lamp at 200 nm however it would be much harder to use here on account of the large amount of scattered visible radiation. The same argument applies to the argon arc, and there is the additional uncertainty of the effects of self-absorption, but since it may be one or two orders of magnitude more intense than the discharge sources it has been regarded as a possible source for the vacuum ultraviolet spectral region.

Table XIII is a guide for the selection of a source according to the criteria laid out at the beginning of this section. For a particular application more data can be obtained from the text and figures given earlier in this report. In addition the text offers a guide to the literature of these sources, which can be of help in computing some of the performance parameters which are not given.

APPENDIX A

APPROXIMATE INTENSITY CALCULATION FOR THE ARGON ARC

These calculations are based on the arc results given by Olsen[46] and employ several simplifying assumptions. The consequencies and validity of these assumptions were not investigated carefully; the result shown in Figure 5.2, therefore, indicates that a more careful study of the question would be worthwhile.

With a current of 400 amperes, and a pressure of 1.1 atm., Olsen measured a core temperature of 26,000°K.[46] There are large temperature gradients as indicated in Figure 2.31. Marked changes would be found by varying the arc current but the arc was designed to operate most stably at 400 amperes. The regions emitting peak intensities depend on the radiation wavelength. Peak line intensities for the ArI lines are obtained in regions outside the core, where the density of ArI is higher. Peak continuum radiation is emitted by the core where the electron density is highest.

The continuum emission from the arc is due to free-free and free-bound electron transitions. The Kramers-Unsold theory has been found to give quite good agreement between theory and experiment.[109,110] When the contributions from the free-free and free-bound electron transitions are summed, then for free-bound transitions in which the atomic energy levels are so close together that they may be treated as a continuum, the emission intensity (per unit frequency interval) is independent of wavelength, just varying as $n_i n_e/(kT)^{1/2}$.[10] When the recombining electrons fall into lower states, where it is no longer correct to treat the levels as a continuum, then an exponential decay in intensity is observed (per unit frequency interval) to lower wavelengths,

$$I \alpha \quad \frac{n_i n_e}{(kT)^{1/2}} \quad \exp\left\{ - \quad (\nu_1 - \nu)/kT \right\}$$

where ν_1 is the frequency limit at which the "closely spaced levels" approximation ceases to hold. As ν increases, there comes a point when the population of a new, lower, atomic energy level will contribute to the intensity. At this point the intensity increases suddenly, before resuming a downward trend as λ decreases. Thus, the theoretical profile of emission intensity is a series of steps except at long wavelengths (levels close together) and low wavelengths (after recombination into the atom's first excited state has been included). For the rare gases these steps lie in the visible and near ultraviolet. In theory, there is a step or edge for each energy level (degenerate levels sharing the same edge). In practice, these are rounded due to temperature and pressure broadening. In making calculations one may group these levels, taking a few groups to cover the wavelength range. One of the basic difficulties in making these calculations is the absence of cross section data giving the relative intensities of the emission edges.

Calculations of relative intensities are more reliable than those for absolute values, so the former are made here, fitting the calculations to the intensity given by Olsen for $\lambda = 553.5$ nm.

For this calculation the energy levels of argon were assumed continuous down to $E = 14{,}000\ \mathrm{cm}^{-1}$, E is the difference between the ionization energy and the atomic energy level being considered. Two groups of energy levels were then taken:

> 4P levels with $\Delta E = 20{,}000\ \mathrm{cm}^{-1}$
> 4S levels with $\Delta E = 32{,}500\ \mathrm{cm}^{-1}$
> and the terms for both the $^2P_{1/2}$ and $^2P_{3/2}$ states of the ion included.

The cross sections for recombinations into these levels were estimated as follows:

(a) S states were assumed to have a cross section one-third that of P-states, in accordance with values given for the hydrogen atom[111] and used by Mies.[112]

(b) The cross sections were weighted according to the degeneracy of the ionic states and also the final electronic state.

(c) Each group was given a cross section proportional to the sum of the weighting factors in (b) multiplied by one or three according to (a).

(d) The group of closely spaced levels, treated as the continuum, was arbitrarily weighted to give the intensity at one third of the value at the peak of the first edge, due to the 4P group. This falls roughly into line with the calculation of Mies for Krypton.[21]

The resulting curve was normalized to the value obtained by Olsen at $\lambda = 553.5$ nm. His results showed that there was slight self-absorption at this wavelength. The value of the emission coefficient was found to rise rapidly to 15,000°K and then to remain nearly constant up to 30,000°K. In regions of the arc at 15,000°K, the emission was 8 watt. sterad.$^{-1}$ cm^{-3} nm^{-1}. Assuming an equivalent emitting layer of 5 millimeters, gives the steradiancy, 4 watt sterad^{-1} cm^{-2} nm^{-1}. The self-absorption will increase toward lower wavelengths since this radiation arises through recombination into deeper atomic energy levels. At 10,000°K and upwards, the 4S and 4P grounds of energy levels become appreciably populated and self-absorption can be expected.

The results of the calculation are shown in Figure 5.2.

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